Observation of Bifurcation to Chaos in an All-Optical Bistable System

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The bifurcations to periodic and chaotic states in an all-optical bistable system proposed by Ikeda *et al.* have been observed. A single-mode optical fiber was used as a nonlinear medium in a ring cavity. The incident beam was the second harmonic of a pulse train from an actively mode-locked and Q-switched yttrium-aluminum-garnet laser whose cavity length was equal to one-half that of the ring cavity. The bifurcation to period-two state was clearly observed at a certain level of the incident power, and further increase in power resulted in a chaotic state.

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Bistability seen in nonlinear optical systems has attracted great interest from both theoretical[1,2] and experimental[3,4] points of view in the last several years for its possible application in devices. On the other hand it is well known that some nonlinear systems far from equilibrium go through a sequence of transitions from a stationary state to periodic self-pulsing states and finally to nonperiodic chaotic states, when the parameters involved are varied.[5,6] Recently one of the present authors has theoretically shown that such instabilities will occur in an optical bistable system.[7,8] The first observation of chaos in an optical system was in a hybrid system, reported by Gibbs *et al.*[9] Later they carefully compared their experimental results with theory to obtain fairly good agreement between them, and found a new regime of instabilities.[10] Since the experiments performed so far were limited to hybrid optical systems in which the delayed feedback was achieved with the help of a computer or electric circuits,[9-11] an experiment in an all-optical system has been considered an urgent matter.

The bifurcations are caused by the interference between the incident field and the cavity field which suffers a nonlinear phase shift in each travel through the cavity. For the realization of chaos in an all-optical system a nonlinear phase shift $\Delta\varphi$ of order unity is required; therefore we need an intense field, a medium with a large nonlinear refractive index, or a long medium path length. One method to obtain a sufficiently high intensity is to focus a beam into a small spot size, but this involves very complicated problems such as intensity distribution through the beam cross section, self-focusing and diffraction of the beam, etc. To avoid these difficulties and meet the necessary conditions mentioned above, we used a single-mode optical fiber as a nonlinear medium in a ring cavity. It has been theoretically[12] and experimentally[13] proved that light propagation in a single-mode optical fiber can be treated by a plane-wave description even in a nonlinear regime. Moreover, use of a single-mode optical fiber with a very small core diameter facilitates the attainment of a high photon density with a laser of a moderate output power. As a light source having a power for the sufficient phase shift, we used a mode-locked pulse train. The successive pulses from the train can realize repeated interference in the ring cavity if the period of the mode-locked pulses and the transit time of the ring cavity are matched.

Our experimental setup is indicated in Fig. 1. The incident beam was the second harmonic (532 nm) of the output pulse train from an actively mode-locked and Q-switched yttrium-aluminum-garnet laser.[14] The pulse width was 140 psec (full width at half maximum), the spectral width was 3 GHz (close to transform limit), the separation between pulses was 7.6 nsec, and the width of the envelope of the pulse train was about 450 nsec. The optical length of the ring cavity, including 120 cm of the single-mode optical fiber (ITT, Type T-1601) with a core diameter 4 μm,

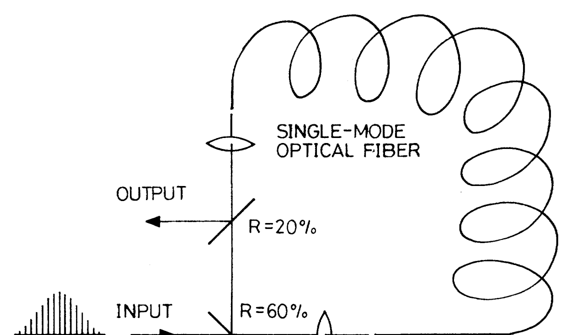

FIG. 1. Schematic diagram of the experiment.

was carefully adjusted so that one transit time t_R was precisely equal to the period of the mode-locked pulses (7.6 nsec). The nonlinear refractive index n_2 of the core of the silica glass fiber is 1×10^{-13} esu. The beam coupling into and out of the fiber was achieved by $10\times$ microscopic objective lenses. The polarization of the output beam from the fiber was adjusted to be linear in the same direction as the input, and was perpendicular to the plane of Fig. 1. The reflectivity of the mirror was 60%, and the total reflectivity of the two surfaces of the glass plate used for the output monitor was 20%. The total loss per round trip in the ring cavity due to the two objective lenses, the glass plate, and the imperfect coupling of the beam into the fiber was about 60% (the loss by the fiber is negligibly small). The reflectivities and the loss of the ring cavity give us a value of 0.4–0.5 for the parameter B of Ref. 8 which characterizes the size of the feedback of the cavity. The uncertainty in B arises from the difficulty in measuring the coupling efficiency of the feedback beam into the fiber.

Figure 2 shows the envelope patterns of the output from the ring cavity for three different peak powers of the input pulse train: 50, 160, and 300 W for (a), (b), and (c), respectively. When the input power is low, (a), the output pattern is Gaussian shaped like the input, but in (b) we see in the center part of the envelope that two envelopes are traced by alternate pulses. At the input power level of (b), we calculated A^2B of Ref. 8, which characterizes the onset of chaos, obtaining a value close to unity, and the nonlinear phase shift due to the propagation through the 120-cm optical fiber was calculated at the peak to be about π. Further increase in power results in a rather random modulation on the envelope as shown in (c). The center part of the envelope of Fig. 2 is shown in Fig. 3 for respective input power levels of (a), (b), and (c). In Fig. 3(b) we clearly see the period-two state, where the period is twice the transit time of the ring cavity, and in (c) the envelope becomes chaotic. Since each single pulse in an input pulse train is not square but Gaussian shaped, it is theoretically expected that in the chaotic regime, where the input power is high, each output pulse has a very complicated structure. In fact the preliminary measurement of the output spectrum showed a rather abrupt spectral broadening when the input power was increased to the level of chaos. As a slow detector (rise time ~ 1 nsec) averages out this complicated modulation, the envelope of the output pulse train appears rather smooth in the chaotic state of Fig. 3(c).

We numerically calculated the output envelopes expected in our experiment by using the difference equation for the cavity field $E(t)$ [Eq. (4) of Ref. 8]:

$$E(t) = A(t) + BE(t - t_R)\exp\{i[|E(t-t_R)|^2 - \varphi_0]\},$$

where φ_0 is the mistuning parameter. We assumed a Gaussian-shaped pulse train as in the

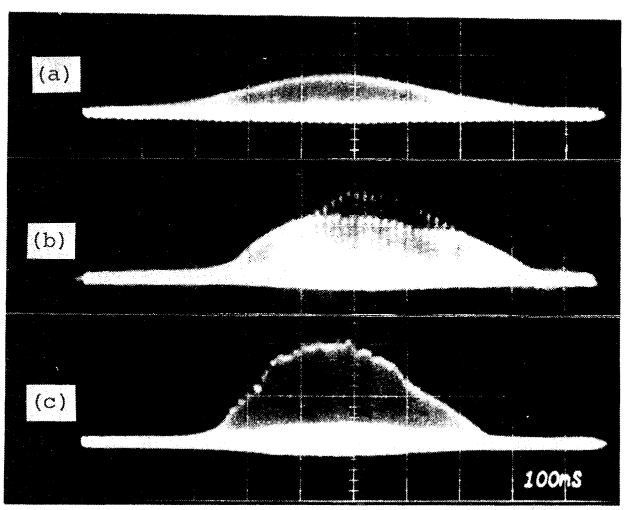

FIG. 2. Oscilloscope traces of the output from the ring cavity. The power levels of the input to the cavity are 50, 160, and 300 W for (a), (b), and (c), respectively. Horizontal scale is 100 ns/div.

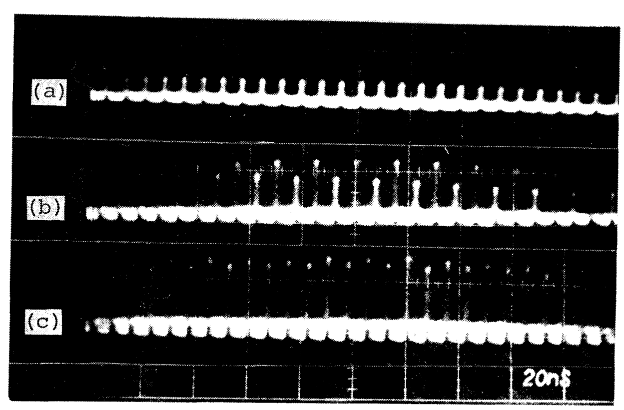

FIG. 3. Oscilloscope traces of the center part of the output envelope from the ring cavity for respective input power levels of (a), (b), and (c) in Fig. 2. Vertical gain of the oscilloscope in (c) is reduced by a factor of 2 from that in (a) and (b). Horizontal scale is 20 ns/div.

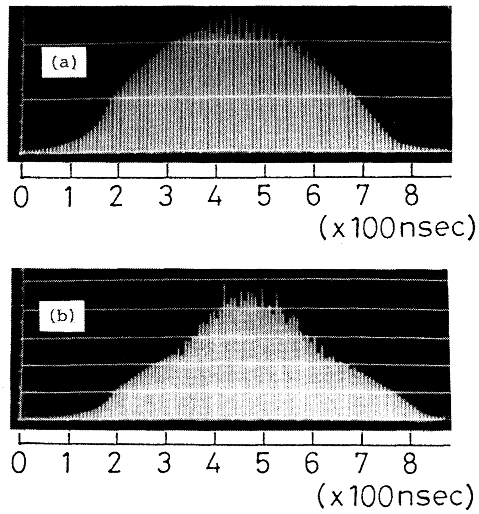

FIG. 4. Computer simulations of the output from the ring cavity: (a) period-two state where $\varphi_0=\pi/2$, $B=0.4$, $A^2B=1.3$, and (b) chaos where $\varphi_0=\pi/2$, $B=0.4$, $A^2B=2.5$.

experiment for the incident field $A(t)$. The results of the computer simulations are indicated in Fig. 4 under the conditions $\varphi_0=\pi/2$, $B=0.4$, and $A^2B=1.3$ for (a), and $A^2B=2.5$ for (b), respectively, where A is the value of $A(t)$ at the peak. In the simulation the nonlinear refractive index of the fiber was assumed to follow the field adiabatically (fast limit of medium relaxation). The essential features of the period-two state and the chaos are very well reproduced in Figs. 4(a) and 4(b).

The range of the cavity length for the occurrence of the bifurcations is very limited. In fact, when the ring cavity was lengthened or shortened

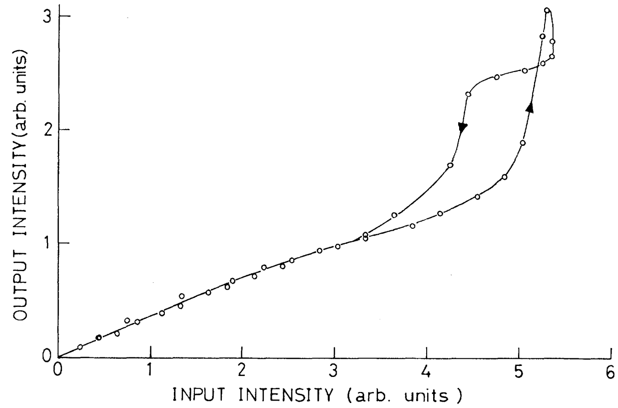

FIG. 6. Output vs input intensity in the case of the oscilloscope trace of Fig. 5(a) when the ring cavity is lengthened by 6 mm.

by more than a few millimeters, the bifurcations such as in Fig. 3 did not occur at any input power level and the envelope became smooth. The shape of this smooth envelope changes with the value of the mistuning parameter φ_0. As the fluctuation in the length of the ring cavity was of the order of one wavelength per second, the change in φ_0 in a single input pulse train (~450 nsec) was negligible. Figures 5(a) and 5(b) show two examples of the output envelope pattern for two different values of φ_0, when the cavity is lengthened by 6 mm at the input power level equal to that of Figs. 2(b) and 3(b). Again the features observed experimentally are reproduced by computer simulations as shown in Figs. 5(c) and 5(d), where $B=0.4$, $A^2B=1.1$, and the values of φ_0 are different for 5(c) and 5(d). The output versus input intensity in the case of Fig. 5(a) is

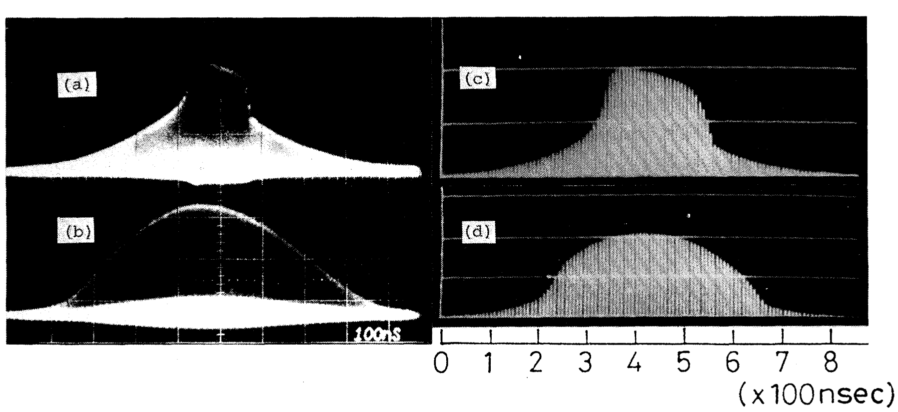

FIG. 5. (a), (b) Two examples of oscilloscope traces of the output from the ring cavity (the peak input power is 160 W), and (c), (d) their computer simulations ($B=0.4$, and $A^2B=1.1$), when the cavity is lengthened by 6 mm. φ_0 is different between (a) and (b), and between (c) and (d).

plotted in Fig. 6. This indicates that bistablelike behavior may appear for some range of φ_0 when the transit time of the ring cavity and the period of the mode-locked pulse train are mismatched. The mismatching reduces the extent of overlap and thus the interaction between successive pulses in a pulse train. This could be the cause of the smoothing and the appearance of the bistability when the cavity length is mismatched.

Other nonlinear processes which are expected to occur in the fiber are stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The threshold power of SBS in our single-mode optical fiber of length 120 cm was about 20 W, one order of magnitude lower than the onset of the bifurcations. But SBS is possible only in the direction opposite to the input beam, and therefore SBS is strongly suppressed for a pulse train of short pulses. On the other hand SRS can build up in the forward direction, and it actually occurred in our ring cavity at a few times higher input power level than the onset of the chaos.

In conclusion, the use of the mode-locked pulse train and the single-mode optical fiber was the key feature of the present experiment. In this system the bifurcations to the periodic and chaotic states in an all-optical system were realized.

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Realization of a Stable and Highly Efficient Gyrotron for Controlled Fusion Research

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The innovation of adding a beam prebunching section at the input to the cavity of a millimeter-wave gyrotron oscillator has yielded outstanding improvements in mode control and device efficiency. These results constitute a technological breakthrough which greatly improves prospects of developing gyrotrons with megawatt average power ratings as will be required for bulk heating of plasma in controlled thermonuclear reactors.

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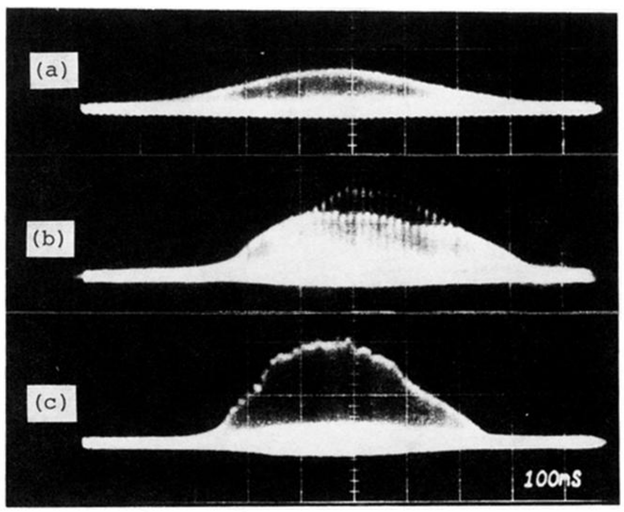
Electron-cyclotron resonance heating (ECRH) has proven to be a promising method of heating of fusion research plasmas. This is due in part to the availability of a new type of powerful millimeter-wave source, the gyrotron, and in part to successful demonstration of ECRH in tokamaks,[1,2] bumpy torus devices,[3,4] and magnetic mirrors.[5,6] ECRH now constitutes a key phase in many fusion research programs. For example, the formation of the hot-electron ring in Elmo bumpy torus[7] and the creation and sustainment of the thermal barriers[8] in the tandem mirror depend critically on this method of heating. Further, localized rf power deposition in electron velocity space



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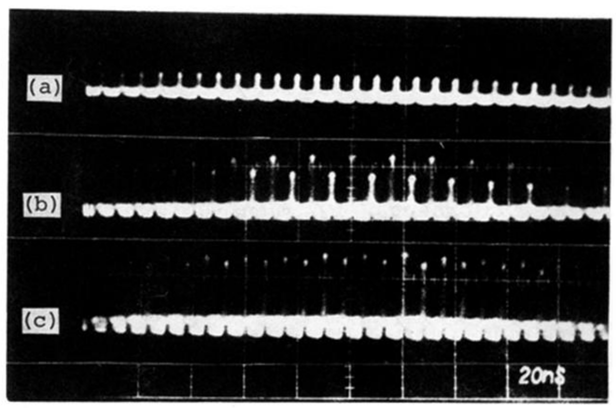

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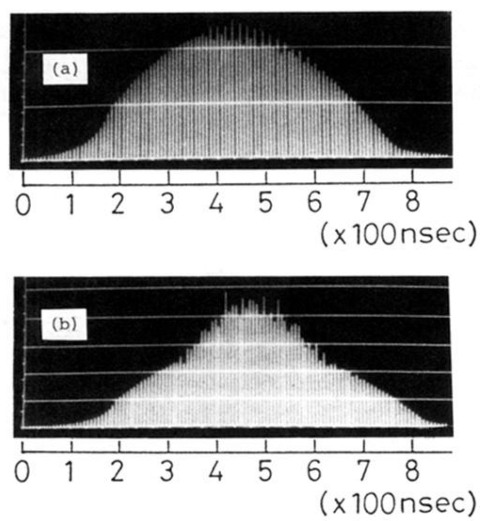

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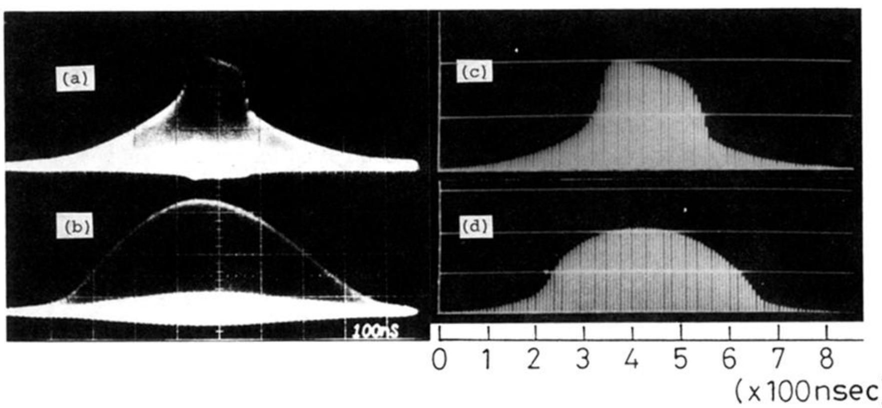

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