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Optical bistability in a fiber ring cavity with synchronous pulsed pump: anomalous and normal dispersion

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Passive fiber cavities are basic nonlinear optical systems that are described by simple models and however they have a rich spectrum of complex behaviors (optical bistability, period-doubling bifurcations, chaos, modulational instability). From a practical point of view its study would have direct implications in the understanding of more complex cavity-based optical devices such as fiber lasers, Fabry-Perot lasers or APM lasers. Moreover, passive fiber cavities have potential applications in telecommunication as ultra-short pulse generators [1] and as optical memories using its bistable behavior. More concretely, this work is a contribution to the study of those bistable behaviors with pulsed input, so the device studied could be used for pulsed optical memory storage.

The device, schematically depicted in fig. 1, consists of a ring cavity made of nonlinear passive single-mode optical fiber with a length L, and two lineal directional couplers with transmission and reflection coefficients θ^2 and ρ^2 respectively ($\theta^2 + \rho^2 = 1$). To simplify, we consider no intensity losses in both couplers.

The temporal separation distance between the input pulses is equal to the time needed by each pulse to make a round trip (t_R), i.e. the so called *synchronous* pulsed pump.

The equations that describe the system are [2]:

$$i\partial_Z U_n(Z,T) - (\eta/2)\partial^2_{TT} U(Z,T) + \mid U_n(Z,T) \mid^2 U_n(Z,T) = 0 \tag{1}$$

$$U_{n+1}(T) = \theta U_{IN}(T) + \rho^2 U_n(1,T) e^{-i\delta_0} \tag{2}$$

$$\mid U_{OUT,n}(T) \mid^2 = \theta^2 \mid U_n(0,T) \mid^2 \tag{3}$$

with $Z = z/L$; $\tau = t - z/v_g$; $T = \tau/sqrt(\mid \beta'' \mid L)$; z is the longitudinal coordinate along the ring axis; $U_n(Z,T) = \sqrt{\gamma L} E_n$ and $U_n(T)$ is just after the first coupler ($z = 0$); n is the round trip (n = 1, 2, ...); E is the envelope of the pulses in the fiber; U_{IN} and U_{OUT} are the scaled input and output respectively; v_g is the group velocity of the pulse with a carrier frequency ω_0; β'' is the group-velocity dispersion; $\eta = \beta''/\mid \beta'' \mid$ is the sign of the dispersion; $\gamma = \omega_0 n_2/(cA_{eff})$; n_2 is the nonlinear refractive coefficient; A_{eff} is the effective core area; δ_0 is the detuning of the cavity with respect to linear resonances. We work with incoming pulses $U_{IN}(T) = A\,\mathrm{sech}(T)$.

The numerical method used to solve the eq.(1) is the *split step Fourier* method. The essence of this method is to propagate the field along z in a dispersive and in a nonlinear way independently. We will use the symmetric version because it gives an error of order h^3 with h the step of propagation in z. In a more specific explanation of the method we can consider eq.(1) in an operational way [3]: $\partial_Z U = (\hat{D} + \hat{N})U$ with $\hat{D} \equiv -i(\eta/2)\partial^2_{TT}$ the dispersive operator and $\hat{N} \equiv i\gamma \mid U \mid^2$ the nonlinear one. The field after a propagation distance h is then approximated by:

$$U(Z+h,T) = \exp(\frac{h}{2}\hat{D}) \exp(\int_Z^{Z+h} N(U(Z',T))dZ') \exp(\frac{h}{2}\hat{D}) U(Z,T) + O(h^3) \tag{4}$$

The error is due to the nonconmutativity of the two operators. The operator $\exp((h/2)\hat{D})$ is applied on the field U in Fourier space using the FFT algorithm. As $\hat{N}$ depends on $U(Z,T)$ we are not able to integrate the nonlinear term. We approximate the integral by $hN(U_D(Z+h/2,T))$ where $U_D(Z+h/2,T)$ is the field propagated only in a dispersive way [4].

In the good cavity limit [5][6] with a *cw pump* (i.e. no dependence on T) the input-output curve of the stationary states of the system is described by: $X = Y^3 - 2\Delta Y^2 + (\Delta^2 + 4)Y$ with $X = 8 \mid U_{IN} \mid^2 /\theta^4$, $Y = 2 \mid U_{OUT} \mid^2 /\theta^4$ and $\Delta = 2\delta_0/\theta^2$. A critical value of the detuning δ_0 is found. Over that value we find optical bistability (O.B.) and under it an univalued input-output response. Those critical values are:

$\delta_{0,crit} = \theta^2\sqrt{3}$. To be in the range of the good cavity limit we will concentrate our study to high refletion coefficients: $\rho^2 = 0.9 \longleftrightarrow \delta_{0,crit} = 0.17$, $\rho^2 = 0.8 \longleftrightarrow \delta_{0,crit} = 0.34$.

Working with *pulsed pump* we also tried to obtain bistable cycles and the critical values of the detuning with high reflection coefficients.The results are showed below.

Normal dispersion

With normal dispersion for $\rho^2 = 0.9$ we get O.B. with $\delta_0 \geq 0.7$; for $\rho^2 = 0.8$ with $\delta_0 \geq 1.1$ and for $\rho^2 = 0.7$ with $\delta_0 \geq 1.5$. Comparing the results obtained in this dispersive regime with the cw pump case, we can conclude that with pulsed pump the critical detuning to achieve O.B. is much more higher than with cw pump (fig. 2). The intensity (i.e. the peak intensity of the input pulses) needed to switch-on in the bistable cycles is of the same order than with cw pump, but the input switch-off intensity is lower with cw pump (fig. 3).

Anomalous dispersion

With anomalous dispersion for $\rho^2 = 0.9$ we get O.B. with $\delta_0 \geq 0.2$; for $\rho^2 = 0.8$ with $\delta_0 \geq 0.3$ and for $\rho^2 = 0.7$ with $\delta_0 \geq 0.5$. Comparing again the results of this dispersion regime with those obtained with cw pump, we conclude that the critical detuning necessary for O.B. is of the same order in both cases. In fact it is a bit lower in the pulsed case (fig. 4). The input switch-on and switch-off intensities with pulsed pump are much more higher than with cw pump. The input intensity range with bivalued output is larger with pulsed pump.

[1] M. Haelterman, S. Trillo and S. Wabnitz, Electron. Lett. **29**, 119 (1993).

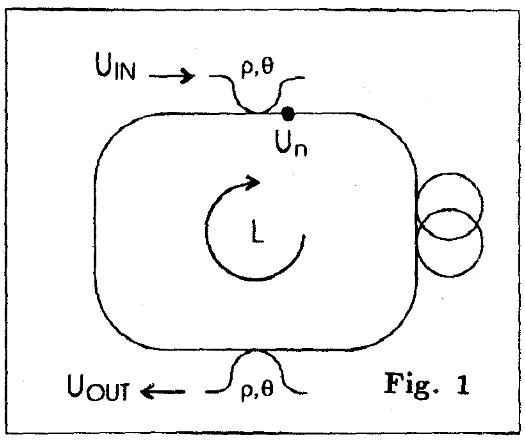
[2] R. Vallée, Optics Comm. **93**, 389 (1992).

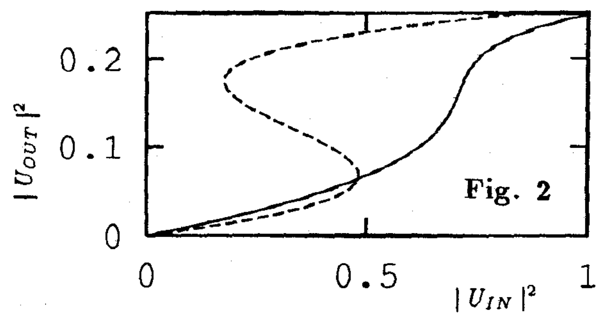
[3] G.P. Agrawal, "*Nonlinear Fiber Optics*", (Academic Press, 1989) and the references cited in chap. 2.

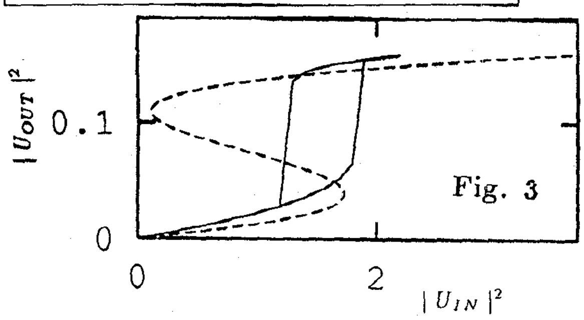
[4] D. Yevick and B. Hermansson, Optics Comm. **47**, 101 (1983).

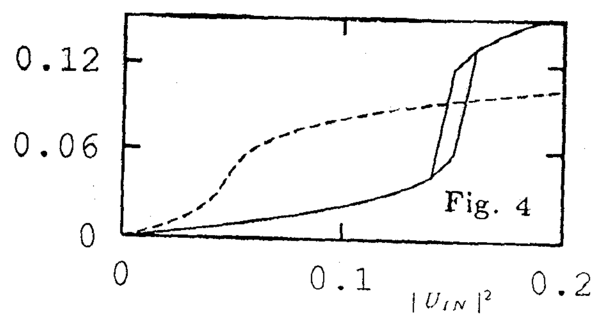
[5] M. Haelterman, S. Trillo and S.Wabnitz, Optics Comm. **91**, 401 (1992).

[6] M. Haelterman, S. Trillo and S. Wabnitz, J. Opt. Soc. Am. B **11**, 446 (1994).









Figures: 1. Scheme of the fiber ring cavity. **2.** Input-output peak intensity curve for $\rho^2 = 0.8$, $\delta_0 = 0.9$ and normal dispersion regime, with pulsed pump (continous line) and cw pump (dashed line). With cw pump we observe bistability and with pulsed pump an univalued curve. **3.** Same as fig.2 but with $\rho^2 = 0.9$ and $\delta_0 = 1.1$. **4.** Same as previous but with $\rho^2 = 0.8$, $\delta_0 = 0.3$ and anomalus dispersion. The critical detunings with this kind of dispersion are of the same order with cw pump and with pulsed pump.