Coupled non-linear microresonator systems: modelling and applications

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***Abstract*—A simple model is used to simulate the dynamic properties of coupled nonlinear microcavities. The model has been checked using a nonlinear finite difference time domain code. We show that two coupled nonlinear cavities with a Kerr nonlinearity can have multistable or self pulsing behaviors. Finally, an application as a positive pulse all-optical memory is proposed.**

I. Introduction

The integration of all-optical signal processing required the miniaturization of active [1] or passive [2], [3] nonlinear photonic devices. Microcavities including microdisks, microrings or photonic crystal nanocavities are of great interest to reach this goal. Passive nonlinear devices based on the optical Kerr effect are intrinsically fast and have low losses [4]. Consequently they could be of great interest for high bit rate optical applications. The coupling of such nonlinear microcavities improves the device performances with respect to single cavity approaches. For example, the bandwidth of fully integrated all-optical reshapers [5] or the efficiency of frequency converters [6] can be increased. In this paper we first review the methods to simulate the response of a nonlinear Kerr microcavity including comparison between coupled mode theory (CMT) and nonlinear finite difference time domain (FDTD) [7]. We then apply the CMT to the case of coupled nonlinear cavities and carry out their linear stability analysis. We show that these systems can have a true multistable behavior which can be used in all-optical switching applications.

II. Nonlinear cavity model

We first study a simple system consisting of a single microcavity made of a third order $\chi^{(3)}$ nonlinear material whose the nonlinear refractive index is denoted n_2 and the optical losses are characterized by τ_0 (Fig. 1). The microcavity is coupled to two bus waveguides with two characteristic coupling times τ_{e1} and τ_{e2}. The time domain variations of the slowly varying cavity mode amplitude $a(t)$ is obtained integrating:

$$\frac{da}{dt} = \left(jq\left|a(t)\right|^2 - \frac{1}{\tau} \right) a(t) + \sqrt{\frac{2}{\tau_{e1}}} s_{in}(t), \qquad (1)$$

$\tau^{-1} = \tau_0^{-1} + \tau_{e1}^{-1} + \tau_{e2}^{-1}$ defines the mode amplitude lifetime, $s_{in}(t)$ the input signal, q is related to the mode volume $\mathcal{V}$ and the effective refractive index n_{eff} of the cavity mode by $q = n_2\omega_0 c/(n_{eff}^2\mathcal{V})$. For a given system τ_0, τ_{e1}, τ_{e2} and ω_0 can be

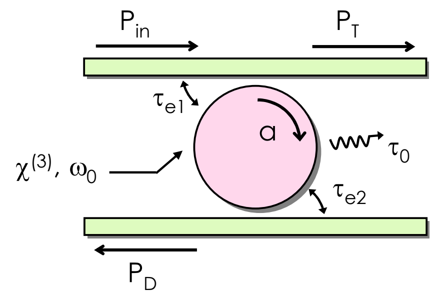

Fig. 1. Single microcaviy coupled to two bus straight waveguides. The cavity is made of a material with a third order susceptibility $\chi^{(3)}$. The output powers are defined by: $P_T = \left|-s_{in} + a\sqrt{2/\tau_{e1}}\right|^2$ and $P_D = 2\left|a\right|^2/\tau_{e2}$.

deduced from a comparison with full numerical calculations such as the FDTD method [8], [9]. Figure 2 gives the fitting of two-dimensional FDTD calculations by the CMT model for the nonlinear bistable microring described in ref. [7]. The calculations have been carried out in the stationary regime at an angular frequency ω with a detuning $\Omega = \omega - \omega_0 = 2.6/\tau$.

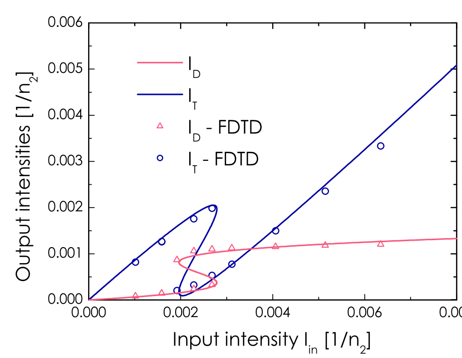

Fig. 2. Full numerical FDTD calculations of the output drop (triangles) and transmitted (circles) optical intensities for a nonlinear microring. We also give the associated CMT fitting curves. Note that here we used two values τ_{e1}^{in} and τ_{e1}^{out} for τ_{e1} to consider the asymmetry and the losses of the coupler.

III. Time domain analysis of coupled cavities

Even though, full numerical calculations are strictly required for the precise design of a device based on a nonlinear

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microcavity, the CMT approach can help to understand the physical properties of more complex devices such as coupled nonlinear cavities. Figure 3 represents a lossless two coupled

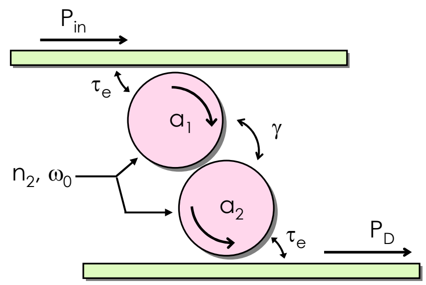

Fig. 3. Two coupled nonlinear microcavities. The two cavity modes are a_1 and a_2. The coupling rate between the two cavities is $1/(2\gamma)$.

nonlinear cavity device, $1/(2\gamma)$ is the coupling rate between the two cavity modes a_1 and a_2. The coupled mode evolution equations derived from the CMT read:

$$\frac{da_1}{dt} = \left(jq\,|a_1(t)|^2 - \frac{1}{\tau}\right) a_1(t) + \frac{j}{2\gamma} a_2(t) + \sqrt{\frac{2}{\tau_e}} s_{in}(t)$$
$$\frac{da_2}{dt} = \left(jq\,|a_2(t)|^2 - \frac{1}{\tau}\right) a_2(t) + \frac{j}{2\gamma} a_1(t). \quad (2)$$

The analysis of the Jacobian of this set of equations gives the dynamical behavior of the coupled nonlinear cavity system described in Fig. 3 [9].

A. Stability analysis

Figure 4, shows the classification of the solutions of system (2) for a coupling rate $\gamma = \tau/9$. For sufficiently large values

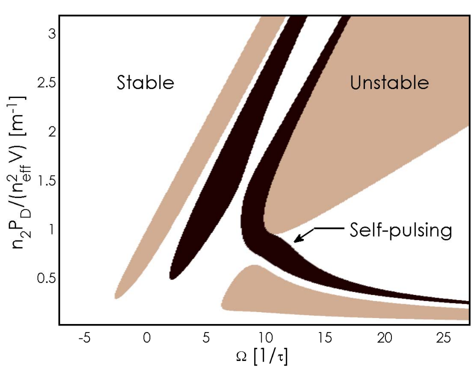

Fig. 4. Classification of the mode amplitude solutions for a two coupled lossless cavity system in the case of $\gamma = \tau/9$.

of detuning, Ω and input power, the coupled cavity system can have a multistable [10] or a self-pulsing behavior [9].

B. Application

We propose here an all-optical switching process relying on the multistability of the two coupled cavity device. The interest of this process in comparison with others based on single cavity approaches is that it requires only positive optical pulse. First a set pulse switches the system from a low to a

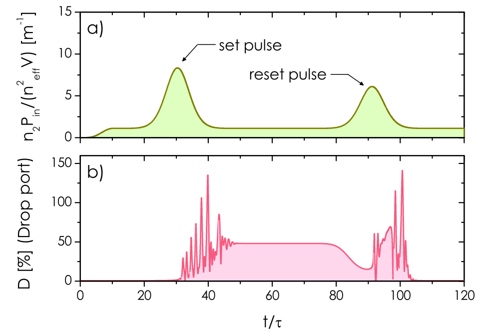

Fig. 5. All optical memory operation of the two cavity device for $\Omega = 11.6/\tau$. a) Input power b) Output drop transmission $D = P_D/P_{in}$.

high transmission state as shown in Fig. 5. Then a second pulse (reset pulse) switches back the system in the low transmission state via a third stable state.

IV. Conclusion

Combined to full numerical calculations, the coupled mode theory is a simple tool allowing the dynamical response of coupled nonlinear cavities to be evaluated. We apply this model to show that coupled nonlinear cavities can operate as an all-optical memory switchable with positive pulses.

Acknowledgment

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