Simple geometry for symmetry breaking observation in grating coupled Kerr waveguide

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In this study we propose a new scheme to observe the symmetry-breaking dynamics between right and left counter-propagating fields in Kerr resonators. The use of a grating to couple light inside the resonator allows a single-beam geometry. In this way, the issue of designing a perfectly symmetrical twin-beam setup is suppressed. The coupling efficiency of this structure is evaluated through numerical modelling in linear regime. We analytically derive the equations ruling the nonlinear dynamics of the counter-propagating fields and demonstrate the symmetry-breaking behaviour.

Introduction

The dynamics of optical Kerr resonators have been widely studied and it is well known that they can exhibit multistability. One of their most striking ability arises when they can be feeded by several components [1]. Indeed, pumping the cavity with several fields with different polarization or propagation directions transforms the nonlinear coupling between these components into a new parameter driving the cavity behavior. Thus injecting symmetrical conditions (components of equal powers) can end with asymmetrical steady-state and these systems could provide key functions, such as flip-flop operations [2] in all-optical systems.

This kind of symmetry breaking can be studied in many configurations. For example, it is expected to appear in optical fiber loop cavities between polarization components [3], it was observed recently between coupled micro-cavities in photonic crystals [4]. One of the first imagined scheme was a Fabry-Perot cavity where the two counter-propagating fields in the corresponding waveguide were pumped with a twin-beam system [5]. Unfortunately, setting up such a configuration is complicated and no experiment has been performed. In this paper we propose a simple single-beam scheme using a grating to couple light in the resonator and observe this left-right symmetry-breaking.

In the first part we demonstrate the ability of the grating to feed the cavity symmetrically. In the second one we anatically study the nonlinear behavior of the new scheme an demonstrate the symmetry-breaking dynamics.

Linear modeling

The geometry is described in Fig.1. The principle is close to the one defined in Ref.[5]. Using a grating to couple light inside the resonator instead of a prism makes a twin-beam injection useless. A similar configuration was proposed in Ref.[6] but the grating was

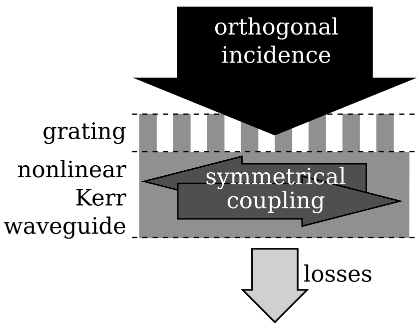

Figure 1: Scheme of the proposed experiment.

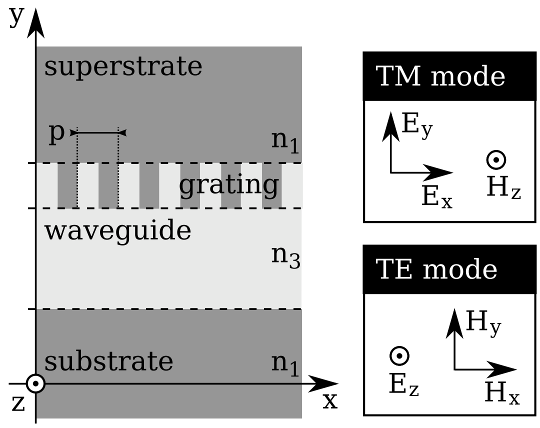

Figure 2: Notations.

used as a reflector for non-orthogonal injection. In our study, orthogonal incidence on the grating will spontaneously result in a symmetrical left-right counter-propagating coupling inside the waveguide.

In order to characterize the coupling efficiency and the modal behavior, we numerically modeled the structure. Realistic parameters were chosen in the view of future experimental demonstration. The design is depicted in Fig.2. It consists in a 1µm-wide waveguide sandwiched between a glass substrate and a grating engraved superstrate whose refractive index is n_1. The period of the grating is p and its engraving depth is d. The waveguiding structure in between is ideally filled with a Kerr medium whose linear part of the refractive index is $n_3 > n_1$.

The stucture is studied in linear regime to check if resonating modes can be coupled with the superstrate through orthogonal incidence on the grating. The result is depicted in Fig.3 where the first transverse magnetic (TM) and electric (TE) modes are represented.

Fig.3(a) describing TM mode clearly shows that the energy trapped inside the resonating waveguide can escape through orthogonal incidence. Indeed, we can see that this TM mode can escape or (as it is equivalent) be feeded through plane waves propagating with 90° angle, inducing a symmetrical left-right coupling.

The issue that can occur in this geometry is the competition between the left-right symmetry breaking that we want to observe and the polarization symmetry breaking between co-propagating circularly polarized components [5]. This phenomenon must be particularly studied because TM incidence equally feeds right and left-handed rotating components. Actually, asymmetry of the grating implies a different mode for the TE component and a different incidence angle. The TE mode is described in Fig.3(b). It corresponds to an escape/coupling angle of 89.5°. What is of particular interest is the fact that this TE mode exhibits a quality factor $Q_{TE} = 2.0\ 10^2$ and it must be compared to $Q_{TM} = 2.7\ 10^5$. The TE mode, even if it is very close to the TM one in terms of coupling conditions, is weakly guided by the grating engraved structure. This imposes a strong asymmetry on the polarization behavior and the TM polarization is conserved. Every energy transfer on the TE mode would escape quickly: in this configuration, the right-left symmetry breaking won't be perturbed by the polarization instability. In the following, the TE mode won't be considered.

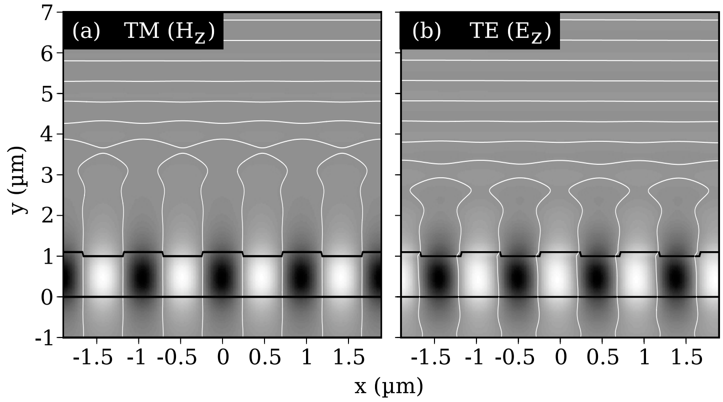

Figure 3: Numerically calculated transverse (a) magnetic and (b) electric modes of the structure. The real part of the fields are represented in grayscale and the nodes are enhanced in white to distinguish the wavefronts. The black line depicts the structure. The optical wavelength is $\lambda = 1.5\mu\text{m}$, $n_1 = 1.5$, $n_3 = 1.64$, $p = 0.95\mu\text{m}$, $d = 0.1\mu\text{m}$.

Nonlinear dynamics

Thanks to the TM linear model, we can extrapolate the corresponding coupling and loss factors ρ and α for the resonator's mode. Given these characteristics, we can use the analytical method used in Ref.[5] [1].
The incident $E_i(x)$ and transmitted $E_t(x)$ fields are defined with their counter-propagating components : $E_i(x) = a(x)e^{j\beta_r x} + b(x)e^{-j\beta_l x}$ and $E_t(x) = r(x)e^{j\beta_r x} + l(x)e^{-j\beta_l x}$
where β_l and β_r are the propagation constant of the left and right components. Using these definitions and assuming the slowly varying approximation ($\partial^2 r(x)/\partial x^2 \approx 0$ and $\partial^2 l(x)/\partial x^2 \approx 0$), the model reads [5]:

$$2j\beta_r \partial r(x)/\partial x + \left(j\alpha^2 - \delta_r^2\right) r(x) + \gamma r(x)\left[|r(x)|^2 + 2|l(x)|^2\right] = j\rho^2 a(x) \quad (1)$$

$$-2j\beta_l \partial l(x)/\partial x + \left(j\alpha^2 - \delta_l^2\right) l(x) + \gamma l(x)\left[|l(x)|^2 + 2|r(x)|^2\right] = j\rho^2 b(x) \quad (2)$$

where $\delta_r = \beta_r^2 - \beta^2$ and $\delta_l = \beta_l^2 - \beta^2$. Now we assume plane-wave approximation ($r(x)$, $l(x)$, $a(x)$, $b(x) = r, l, a, b$), symmetrical injection ($a = b$ and $\Delta_r = \Delta_l = \Delta$) and we can reach, as in Ref.[5]:

$$(R - L)\left[R^2 + RL + L^2 - 2\Delta(L + R) + \Delta^2 + 1\right] = 0 \quad (3)$$

with $R = |r|^2/\alpha^2$, $L = |l|^2/\alpha^2$, $A = |a|^2/\rho^2$, $B = |b|^2/\rho^2$ and $\Delta_{r,l} = \delta_{r,l}^2/\rho^2$.
Finally we get an algebraic description of the steady-states of the resonator. Solving Eq.(3) results in the well-known bifurcation diagram depicted in Fig.4. Before the bifurcation point we clearly see the S-shape implying bistability but symmetrical (R=L) regime. For higher input power conditions, this symmetrical state becomes unstable and the only stable ones are asymmetrical ($R <> L$). Thus for high power conditions, the initial symmetry will be broken. The system will work in an asymmetrical regime depending on initial perturbations or switching mechanisms.

[1] In Ref.[5], as the compared fields are input and output fields outside the cavity, $\alpha = \rho$

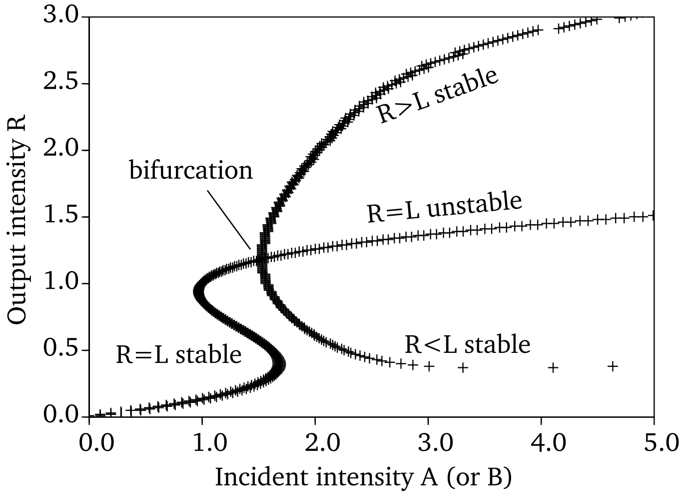

Figure 4: Bifurcation diagram : output intensity of the right (R) component versus input intensity A. $A = B$, $\Delta = 3$.

Conclusion

In this paper we proposed a simple scheme to perform the experimental observation of the left-right counter-propagating symmetry-breaking dynamics in Kerr waveguides. One the one hand we demonstrated that using a grating and orthogonal incidence to achieve the coupling allows for symmetrical condition in the waveguide. On the other hand we derived the analytical study of the corresponding resonator and demonstrated symmetry-breaking dynamics.

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