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A DIRECTIONAL COUPLER WITH PARAMETRIC AMPLIFICATION AS AN ALL OPTICAL SWITCHER[1]

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It is shown that a directional coupler containing parametric amplifying medium in one or both channels can realize an all optical switching device.

The linear directional coupler has been extensively studied in connection with the possibility of realization of electro-optical devices such as frequency selectors, modulators, electro-optical switchers etc. The coupler consists of two adjacent, parallel waveguides. When e. m. radiation is guided inside the structure, exchange of power between the two guides is possible because of the evanescent field between the guides [1-5]. Recently a number of papers have been devoted to the behaviour of nonlinear directional couplers when a third [6, 7] or second order nonlinearity is present inside the structure [8-10].

In the present paper we discuss the propagation of a quantum field in a coupler when the channels contain parametric amplifying medium. This situation can be realized if one (or both) channel is made of a second order nonlinear material realizing a parametric process (down conversion). The advantage of introducing the amplifying medium is the possibility of balancing the coupling constant and the amplifier gain so that the excessive noise can be reduced [11].

First we consider the structure with two coupled lossless amplifiers described by coupling constant K and by an amplification factor g. Generalizing the classical coupling equations assuming strong and nondepleting pump the following equations of evolution of the field can be obtained:

$$\frac{d\hat{a}}{dz} = -iK\hat{b} - ig\hat{c}^{\dagger}, \quad \frac{d\hat{c}^{\dagger}}{dz} = ig\hat{a}, \quad \frac{d\hat{b}}{dz} = -iK\hat{a} - ig\hat{d}^{\dagger}, \quad \frac{d\hat{d}^{\dagger}}{dz} = ig\hat{b}, \tag{1}$$

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where $\hat{a}$ and $\hat{b}$ are the annihilation operators for the field of the same frequency, guided inside the channels a and b, $\hat{c}^\dagger$ and $\hat{d}^\dagger$ are the creation operators of the idler modes coupled through the amplifying mechanism to the modes a and b. The coupling between the idler modes is supposed to be negligible. Here it is also assumed that all the phase matching conditions are fulfilled.

The solutions of Eq. (1) for the signal operators are

$$\begin{aligned}\hat{a} &= u(z)\hat{a}_0 + iv(z)\hat{b}_0 - iw(z)\hat{c}_0^\dagger - x(z)\hat{d}_0^\dagger,\\ \hat{b} &= u(z)\hat{b}_0 + iv(z)\hat{a}_0 - iw(z)\hat{d}_0^\dagger - x(z)\hat{c}_0^\dagger,\end{aligned} \tag{2}$$

where $\hat{a}_0$, $\hat{b}_0$ are the input operators, $u(z)$, $v(z)$, $w(z)$, $x(z)$ are space dependent functions:

$$\begin{aligned}u(z) &= \cosh(rz)\cos(Kz/2) - \tfrac{K}{2r}\sinh(rz)\sin(Kz/2),\\ v(z) &= -\cosh(rz)\cos(Kz/2) - \tfrac{K}{2r}\sinh(rz)\sin(Kz/2),\\ w(z) &= \tfrac{g}{r}\sinh(z)\cos(Kz/2), \qquad x(z) = \sinh(z)\sin(Kz/2),\end{aligned} \tag{3}$$

where $r = \sqrt{g^2 - K^2/4}$. Solutions of similar form can be found for the idler modes as well. Using these equations the evolution of the characteristic function, defined as

$$\chi(\eta) = \mathrm{Tr}\left[\hat{\rho}\ \exp(\eta\hat{a}^+)\ \exp(-\eta^*\hat{a})\right], \tag{4}$$

where $\hat{\rho}$ is the density operator of the system, can be obtained for all the modes. Knowing the characteristic functions one can easily follow some peculiarities of the quantum statistics related to the process. There are two different operational regimes. Let us start with the case when $g > K/2$, i.e. the amplification dominates the interaction. We find that even if there is no input into any modes there is output signal at the end of the guides. For example, the mean value of photon numbers in the mode a is given by the following expression

$$\langle\hat{n}_a(l)\rangle = |\, w(l)\,|^2 + |\, x(l)\,|^2 = \frac{g^2}{r^2}\sinh^2 rl, \tag{5}$$

where l is the length of the coupler. This signal shows thermal noise statistics and the noise grows along the guide without oscillation. In the other regime, when $g < K/2$, the coupling dominates. In this case the spatial functions exhibit periodic behaviour. Now even without any input we may have a noise in channel a, but it oscillates depending on the length of the coupler. When the relation

$$gl = \sqrt{(Kl/2)^2 - (n\pi)^2}, \quad n = 1, 2... \tag{6}$$

among g, l and K is fulfilled there is no excessive noise. As a consequence the length of switching can be modified by changing the amplitude of the pump.

Now let us consider the configuration when the amplified medium is present only in channel a of the coupler. In this case the equations describing the propagation

$$\frac{d\hat{a}}{dz} = -iK\hat{b} - ig\hat{c}^\dagger, \quad \frac{d\hat{c}^\dagger}{dz} = ig\hat{a}, \quad \frac{d\hat{b}}{dz} = -iK\hat{a}, \tag{7}$$

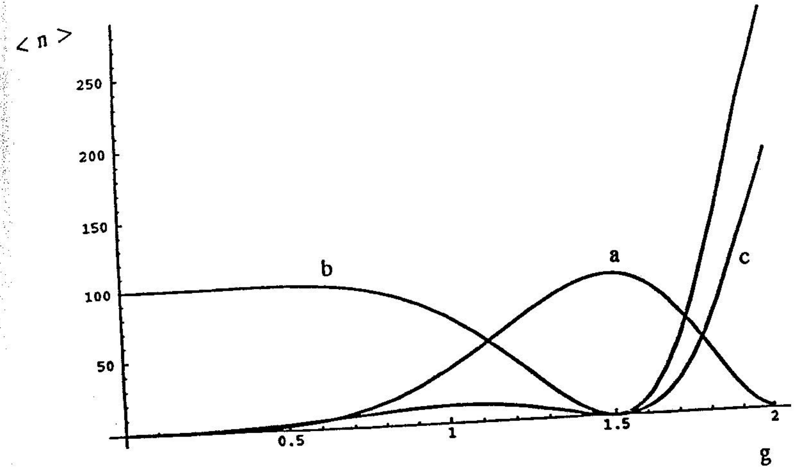

Fig. 1. The output mean number of photons in modes a,b and c as a function of the gain factor g (in π/l units) for an asymmetric device in under threshold operational regime. The coupling constant $K = 5\pi/2l$. The input mean photon into channel a is $\langle\hat{n}\rangle = 100$. For two g values a complete switch without any additional noise is reached: for $g = 0$ the energy comes out from the channel b, and for $g = 3\pi/2l$ from the channel a.

and the solutions are obtained in the form

$$\begin{aligned}\hat{a} &= u_a(z)\hat{a}_0 + v(z)\hat{b}_0 + w_a(z)\hat{c}_0^\dagger,\\ \hat{b} &= u_b(z)\hat{b}_0 + v(z)\hat{a}_0 + w_b(z)\hat{d}_0^\dagger,\\ \hat{c}_0^\dagger &= u_c(z)\hat{c}_0^\dagger - w_a(z)\hat{a}_0 - w_b(z)\hat{b}_0.\end{aligned} \tag{8}$$

When $g > K$, i.e. the amplification is dominant, there is no switch between the channels, only amplification of the signal and, as before, there is noise generation. When the amplification factor and the coupling constant satisfy $g < K$ the spatial functions in Eq. (9) exhibit periodic behaviour

$$\begin{aligned}u_a(z) &= \cos(sz), & v(z) &= -\frac{iK}{s}\sin(sz)\\ u_b(z) &= -\tfrac{g^2}{s^2} + \tfrac{K^2}{s^2}\cos(sz), & u_c(z) &= -\frac{g^2}{s^2}\cos(sz) + \frac{K^2}{s^2},\\ w_a(z) &= -\tfrac{ig}{s}\sin(sz), & w_b(z) &= \frac{Kg}{s^2}\left[-1 + \cos(sz)\right],\end{aligned} \tag{9}$$

where $s = \sqrt{K^2 - g^2}$.

If there is no amplification (g=0) Eqs. (9) describe the switching characteristics of the linear coupler. In the case of nonzero amplification choosing suitable values of K and g (e.g. $K = 5\pi/2l$, $g = 3\pi/2l$), no switch of modes occurs between the channels and no additional noise is generated inside the structure. Note that keeping the coupling constant $K = 5\pi/2l$ and changing g by some external control from 0 to $3\pi/2l$ one can switch the signal between the channels without introducing additional noise. Moreover, the pump, while causing switching, does not change the total number of photons in the device.

Fig.1 shows the output mean number of photons in modes a, b and c as a function of gain factor g. It can be seen that for two values of g a complete switch without any additional noise is realized.

In conclusion, we have considered the behaviour of a directional coupler with one or both channels containing an amplifying medium. Two operation regimes were found: one, "under threshold", in which the amplification is less "effective" than the coupling between channels; in this regime the solutions, describing the output modes as a function of the coupler length, are periodic, the presence of the amplification factor modifies the length over which the switch occurs. The second regime is "over threshold", here the amplification constant is greater that the coupling constant, no complete switching between channels occurs. In the under threshold regime a suitable combination of the parameters inside the structure can provide conditions under which complete switch of energy between the channels occurs without additional noise. The switch can be controlled by the external pump, realizing a possible scheme for an all optical switching device.

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