Optics Communications 354 (2015) 128–131

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Discussion

Tuning optical spectrum between Fano and Lorentzian line shapes with phase control

Keyu Xia [a,*], Jian-Qi Zhang [b]

[a] ARC Centre for Engineered Quantum Systems, Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia

[b] State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, and Wuhan National Laboratory for Optoelectronics, Wuhan 430071, China

ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form
6 May 2015
Accepted 20 May 2015
Available online 26 May 2015

Keywords:
March–Zehnder interferometer
Phase control
Lorentzian profile
Fano profile

ABSTRACT

Controlling the spectrum of light with a phase has received intensive interest of researchers recently. Here, we study the phase control of the spectral line shape of the output from an optical March–Zehnder interferometer (MZI) with one arm involving a high quality Fabry–Perot cavity. Due to the interaction of the narrow-band light transmitted through the cavity with the broadband light, the spectrum can be tuned from Lorentzian to Fano-like profile with a phase shifter in MZI.

1. Introduction

Fano resonance corresponding to Fano absorption line shapes is a result of the quantum interference originated from the coupling of a discrete energy state (discrete light mode) to continuum of states (lights with continuous spectrum) [1,2]. Typical asymmetric Fano absorption line shapes have been widely studied throughout atomic ionization [3], classical harmonic oscillators [4], light propagation in photonic devices [5,6] and optomechanical system recently [7]. Since Lorentzian profile is the natural line shape due to the quantum system decay, the transition from symmetric Lorentzian (Fano parameter $|q| \to \infty$) to asymmetric Fano profile (finite Fano parameter q) is of interest in fundamental physics and also promises important applications [8,9]. Fano spectrum can be engineered by tuning the coupling strength between a discrete state and a continua [10,11]. More interestingly, tuning spectrum between Lorentzian and Fano line shapes via a phase shift [3,12,13] reveals deep physics in quantum mechanics, which attracts much interests recently.

In this paper, we present a simple, all-optical MZI configuration for demonstrating the phase control of the spectra between Lorentzian and Fano profiles. The narrow-band transmission (discrete mode) of a high-quality Fabry–Perot (FP) cavity interferes with the broadband laser beam on the second beam splitter of March–Zehnder interferometer (MZI). This quantum interference results in a spectral line shape dependent on the relative phase shift between the light beams.

2. Setup and model

The system under our consideration is plotted in Fig. 1, where a coherent laser beam incidents into a highly reflective beam splitter (BS1) [14] and is split into two beams with one beam passing through a high-Q optical cavity and the other experiencing a phase shift θ. Then the two output beams are mixed at the second BS2, and we monitor one of the outputs from the BS2.

Let us consider the line shape of the beam $\hat{a}_4$ detected by the detector D1. We assume the input laser beam $\hat{a}_0$ with frequency ω_{in} and the BS1 with the reflection $\eta^2 \approx 0$. The other input $\hat{a}_1$ is a vacuum field, and hence its normally ordered correlation is zero, i.e. $\langle \hat{a}_1^\dagger(-\Omega)\hat{a}_1(\omega)\rangle = 2\pi\bar{n}_{th}\,\delta(\Omega+\omega)$ with the thermal excitation $\bar{n}_{th} \approx 0$. Thus the upper and lower beams output from the BS1 are, respectively, given by

$$\hat{a}_2 = i\sqrt{1-\eta^2}\,\hat{a}_1 + \eta\hat{a}_0, \tag{1a}$$

$$\hat{a}_3 = \eta\hat{a}_1 + i\sqrt{1-\eta^2}\,\hat{a}_0. \tag{1b}$$

* Corresponding author.
E-mail address: xiakeyu@gmail.com (K. Xia).

http://dx.doi.org/10.1016/j.optcom.2015.05.042
0030-4018/

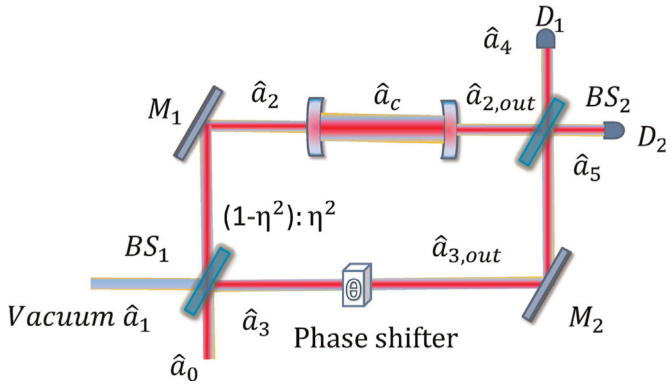

Fig. 1. Setup for tuning the output spectral profile with phase shift. A laser beam $\hat{a}_0$ is split by the first BS into the upper and lower beams. Another input $\hat{a}_1$ of this BS is vacuum field. The phase of the lower one is shifted by θ, while the upper one passes through an optical cavity with a negligible intrinsic loss $\kappa_i \approx 0$. Then the two beams are mixed via the second BS to beams $\hat{a}_4$ and $\hat{a}_5$, and then detected by detectors 1 and 2. The first beam splitter is highly reflective such that the reflection $\eta^2 \approx 0$.

The upper beam $\hat{a}_2$ drives an optical cavity mode $\hat{a}_c$ with a coupling strength κ_{ex} and the cavity mode leaks out to the MZI with two identical rates κ_{ex} from two sides. For the cavity with a resonance frequency ω_c and a total decay rate $\kappa = 2\kappa_{ex}$, the dynamics of the cavity field is governed by

$$\dot{\hat{a}}_c = (-i\omega_c - \kappa)\hat{a}_c + 2\kappa_{ex}\hat{a}_2. \tag{2}$$

According to the input–output relation, we have the output field in the steady state [15]

$$\hat{a}_{2,out}(\omega) = \frac{-2\kappa_{ex}\sqrt{1-\eta^2}\,\hat{a}_1(\omega) + 2i\kappa_{ex}\eta\hat{a}_0(\omega)}{(\omega - \omega_c) + i\kappa}. \tag{3}$$

On the other hand, the lower beam going through the tunable phase shifter becomes

$$\hat{a}_{3,out}(\omega) = e^{i\theta}(\eta\hat{a}_1(\omega) + i\sqrt{1-\eta^2}\,\hat{a}_0(\omega)). \tag{4}$$

The two beams are mixed at a 50:50 beam splitter (BS2), yielding the output

$$\sqrt{2}\,\hat{a}_4(\omega) = \hat{a}_{3,out}(\omega) + i\hat{a}_{2,out}(\omega) = \left(\eta e^{i\theta} - \frac{2i\kappa_{ex}\sqrt{1-\eta^2}}{(\omega-\omega_c)+i\kappa}\right)\hat{a}_1(\omega) + \left(i\sqrt{1-\eta^2}\,e^{i\theta} - \frac{2\eta\kappa_{ex}}{(\omega-\omega_c)+i\kappa}\right)\hat{a}_0(\omega), \tag{5}$$

whose spectrum is defined as $\langle\hat{a}_4(-\Omega)\hat{a}_4(\omega)\rangle = 2\pi S_4(\omega)\delta(\omega+\Omega)$. Note that the vacuum field $\hat{a}_1$ only adds small noise of a level of vacuum fluctuation to the output spectrum $S_4(\omega)$. For our optical MZI, we consider the case of a strong input, $\eta^2\langle\hat{a}_0^\dagger(\omega)\hat{a}_0(\omega)\rangle \gg 2\pi(1-\eta^2)\bar{n}_{th}$ that

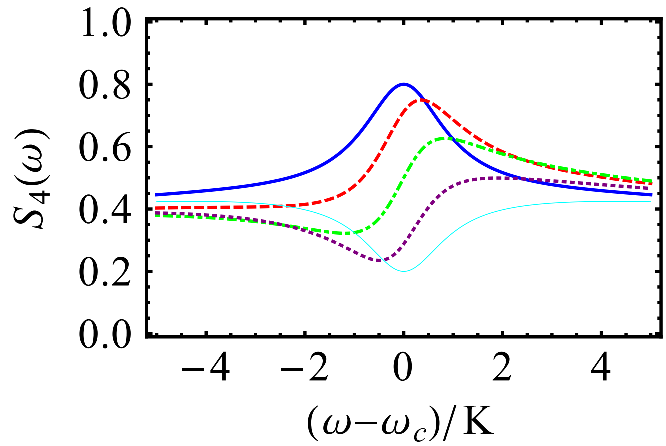

Fig. 3. Output of the power spectra for different phase shift $\theta = \{0, \pi/4, \pi/2, 3\pi/4, \pi\}$ corresponding to $q \approx \{4/3e^{0.5\pi i}, 1.26e^{0.44\pi i}, 1.05e^{0.40\pi i}, 0.8e^{0.40\pi i}, 2/3e^{0.5\pi i}\}$, shown by (solid blue line, dashed red line, dotted-dashed green line, dotted purple line and thin cyan line). $\gamma_{in} = 25\kappa$. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

$$\hat{a}_4(\omega) \approx \frac{1}{\sqrt{2}}\left(i\sqrt{1-\eta^2}\,e^{i\theta} - \frac{2\eta\kappa_{ex}}{(\omega-\omega_c)+i\kappa}\right)\hat{a}_0(\omega). \tag{6}$$

Therefore, to a good approximation, the detected spectrum $S_4(\omega)$ only depends on the coherent input spectrum $\langle\hat{a}_0(-\Omega)\hat{a}_0(\omega)\rangle = 2\pi S_{in}(\omega)\delta(\omega+\Omega)$. We obtain $S_4(\omega) = \frac{1}{2}\mathcal{T}(\omega-\omega_c)S_{in}(\omega)$ with the transmission $\mathcal{T} = |i\sqrt{1-\eta^2}\,e^{i\theta} - 2\eta\kappa_{ex}/((\omega-\omega_c)+i\kappa)|^2$ yielding a standard Fano resonance [1,3]

$$\mathcal{T} = \sigma_0\frac{|q+\epsilon|^2}{1+\epsilon^2}, \tag{7}$$

with $\sigma_0 = (1-\eta^2)$, $\epsilon = (\omega-\omega_c)/\kappa$ and $q(\theta) = i + i(2\kappa_{ex}/\kappa)(\eta/\sqrt{1-\eta^2})e^{-i\theta}$. Throughout our investigations below, we are interested in the critical coupling such that $\kappa = 2\kappa_{ex}$, and subsequently $q(\theta) \approx \eta\sin\theta + i(1+\eta\cos\theta)$. Clearly, Fano parameter q representing the line shape is crucially dependent on the phase shift θ. Further decomposing Eq. (6), we have

$$\mathcal{T} = T_0 + T_1 + T_{\text{Lorentz}} + T_{\text{Fano}}, \tag{8}$$

where

$$T_0 = (1-\eta^2) \tag{9a}$$

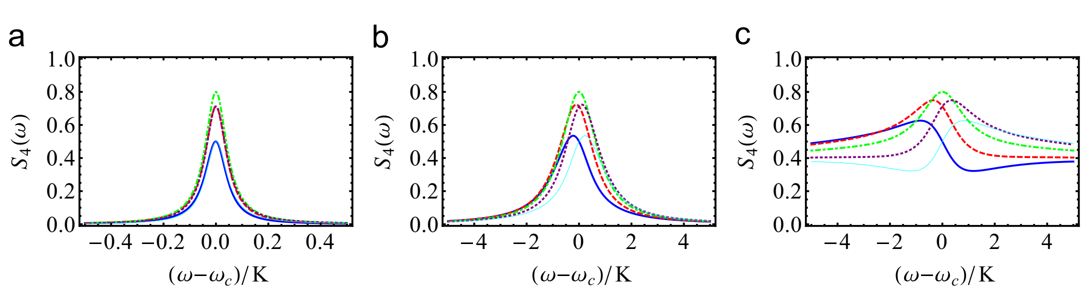

Fig. 2. Phase control of the scaled power spectral profiles for different linewidths of the input laser beam (a) $\gamma_{in} = 0.05\kappa$, (a) $\gamma_{in} = \kappa$, (c) $\gamma_{in} = 25\kappa$. Spectra with different phase shifts are shown by {solid blue lines, red dashed lines, dotted-dashed green lines, dotted purple lines and thin solid lines} for $\theta = \{-\pi/2, -\pi/4, 0, \pi/4, \pi/2\}$ corresponding to $q \approx \{1.054e^{0.6\pi i}, 1.258e^{0.56\pi i}, 4/3e^{0.5\pi i}, 1.26e^{0.44\pi i}, 1.054e^{0.40\pi i}\}$. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)