High Q-factor coupled Fabry-Perot plasmonic nanoresonator

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Abstract

Fabry-Perot (FP) like resonances have been widely described in nanoantennas. In the original Fabry-Perot resonator, a third mirror can be added, resulting in a multimirror interferometer. However, in the case of combination of nanoantennas, it has been reported that each cavity behaves independently. Here, we evidence the interferences between two FP absorbing nanoantennas through a common mirror, which has a strong impact on the optical behavior. While the resonance wavelength is only slightly shifted, the level of absorption reaches nearly 100 %. Moreover, the quality factor increases up to factor 7 and can be chosen by geometric design over a range from 11 to 75. We first demonstrate thanks to a simple analytical model that this coupling can be ascribed to a double FP cavity resonance, with the unique feature that each cavity is separately coupled to the outer medium. Based on this principle, we experimentally illustrate the existence of a high-Q factor resonance originating from the interference between two under-coupled ribbon-shaped nano Fabry-Perot.

1. Introduction

The Fabry-Perot (FP) interferometer was invented in 1899, and consisted of two parallel highly reflecting mirrors, the resonance behavior being characterized by peaks or dips in the transmission and reflection spectra [1]. It has been used in a variety of devices among which optical cavities for lasers or filters [2]. Since this seminal work, various evolutions of the FP interferometer have been introduced among which multi-mirror FP that give birth to a coherent superposition of all the beams [3]. Noteworthy, in most configurations, the mirrors are placed in series. In the past two decades, the development of nanophotonics has given birth to FP-like resonators [4]–[7], in which a guided mode in a metallic cavity has a behavior that is well described by the FP formalism. The advantages of these nanoresonators are their compactness, and the possibility to combine them to design broadband or multiband resonances. It is well accepted that, since these metallic cavities are the siege of localized resonances, they have negligible influences on each other when they are combined [8]–[12].

The two most common plasmonic nanostructures with a FP behavior are the metal-insulator-metal patch nanoantennas (horizontal resonance), and the high aspect ratio nanogrooves (vertical resonance). Both of these resonators are promising for applications ranging from thermal

emission [12],[13], or infrared detection [14] to biosensing [15]. Yet, they suffer from their low quality factor.

In this letter, we introduce double cavity Fabry-Perot like nanoresonator in both vertical and horizontal configurations. It departs from previous works on multimirror FP resonators, as the mirrors are in an hybrid configuration between series and parallel. It gives birth to a spectacular effect where critical coupling, *i.e.* a zero of reflectivity, is obtained while, independently, each of the two cavities is loosely-coupled to free space. Moreover, the quality factor of the double cavity resonators is increased from 11 to 50, well beyond the limit for FP plasmonic nanoresonator [10]. We developed an analytical model that confirms the multimirror FP behavior. Last, but not least, we experimentally demonstrate the coupled Fabry-Perot resonance on a horizontal nanoresonator.

2. Analytical model of the coupled nano Fabry-Perot resonator

We study a periodic double-groove resonator whose period contains two grooves of different heights. While the reflectivity of the periodic single-groove resonators does not go below 85%, the resonance of the double-groove presents a zero of reflectivity and a quality factor of 50 (See Figure 1).

Figure 1 Comparison between the reflectivity of two loosely-coupled single-nanogroove resonators and the reflectivity of a critically coupled resonator composed of the two aforementioned cavities. The geometrical parameters of the cavities, described in the insets, are $d=1 \mu\text{m}$, $w=0.3 \mu\text{m}$, $h_1=0.62 \mu\text{m}$, $h_2=0.55 \mu\text{m}$.

We demonstrate thanks to an analytical model that this coupling can be ascribed to a double FP cavity resonance, with the unique feature that the cavities are coupled to one another through a common mirror.

Figure 2: Scheme of the two-grooves structure and of the different coefficients used in the analytical model. All the coefficients are scalar element.

Using the reflection, transmittion and propagations coefficients represented on the figure 2, we can write the reflectivity of the resonator as a sum of three terms :

$$R = |r_{AA} + G_1 t_{AB} t_{BA} + G_2 t_{AB} t_{BA}|^2$$

Where G_1 and G_2 represent the loop inside the first and second groove and can be written, in the steady state as :

$$\begin{cases} G_1 = \frac{\rho P_1^2 [1 + \rho P_2^2 (t_{BB} - r_{BB})]}{(1 - \rho r_{BB} P_1^2) (1 - \rho r_{BB} P_2^2) - t_{BB}^2 \rho^2 P_1^2 P_2^2} \\ G_2 = \frac{\rho P_2^2 [1 + \rho P_1^2 (t_{BB} - r_{BB})]}{(1 - \rho r_{BB} P_1^2) (1 - \rho r_{BB} P_2^2) - t_{BB}^2 \rho^2 P_1^2 P_2^2} \end{cases}$$

The critical coupling (zero of reflectivity) is then achieved through a three wave destructive interference dictate by the coupling parameter t_{BB} .

3. Experimental demonstration of the coupled nano Fabry-Perot resonance

For this experimental demonstration, we consider horizontal nano FP cavities. An analogy has been demonstrated between the vertical and horizontal nano FP cavities, providing a simple geometry transformation whose principal parameters are summarized in figure 3. The resulting horizontal coupled FP nanostructures studied in this letter are made of three layers as illustrated in the inset of the figure 4.b. A top periodic nanostructure composed of one or several gold ribbons of the same height ($t=50$ nm) but different width denoted by capital letters ($W_A=400$ nm and $W_B=495$ nm) is deposited on two continuous layers, a SiC insulating layer of 280 nm thickness and a gold mirror.

Coupled structures	bi-slit	bi-ribbon
resonance wavelength λ_0	d	$W/2$
critical coupling ($R=0$)	Δd	ΔW
Q-factor	L	h

Figure 3 Correspondence between the bi-slit and bi-ribbon coupled FP cavities.

Figure 2: Measured (dotted) and computed (plain) reflection spectra of (a) single-FP structures and (b) the coupled nano FP structure. Due to the thickness of the SiC layer, the two single FP resonators are under-coupled and their reflectivities do not go below 80%. Due to the coupling between the two FP, the new coupled FP resonance is visible at $\lambda=4.23$ μm with a minimum of reflectivity of 14% and a high Q-factor of 22. The insets represent the different structures

4. Conclusions

The description of the double-groove resonator paves the way to the manipulation and the engineering of the equivalent mirror coupling the two nanocavities, in order to reach multimirror interferences predictions. This structure is also very promising for many practical applications. For example, the wide dielectric layer is needed for nanostructured photodectors or a high Q-factor resonance is useful for gas detection.

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