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Enlarging the spectral accessibility of photonic zero-modes in coupled Photonic Crystal cavities through "image barrier" engineering

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Abstract. Photonic modes resistant to imperfections or perturbations are of paramount importance in many photonic applications. In this context, zero-modes have several advantages. Unfortunately, they are often difficult to observe. In this work, focusing on coupled photonic crystal cavities, we propose and demonstrate a technique that allows control of inter-cavity coupling without introducing concomitant frequency mismatch, thus allowing observation of zero-modes in a non-Hermitian system and testing of their robustness against asymmetries of coupling. This is done through an original "image barrier" engineering approach.

1 Introduction

Zero-modes are intriguing bound states that attracted a lot interest in particular through the elusive case of Majorana zero-modes. In optics, "photonic zero-modes" exhibit zero-energy eigenvalues ($\varepsilon = 0$) in a cavity, or a waveguide, array. As they are symmetry-protected modes they are expected to be robust against coupling disorder, opening thus a wide range of efficient applications. In the Hermitian limit, in which systems are energy conserving, zero-modes are warranted by chiral – or sublattice– symmetry. In non-Hermitian (NH) systems, such as gain/loss coupled cavity arrays, the underlying symmetry is "Particle-hole" symmetry, implying that zero-modes have the freedom to evolve along the imaginary energy axis, and therefore the conditions for their observation are less stringent compared to their Hermitian counterparts [1,2].
Observing and manipulating these zero modes is however not straightforward and the cavity or waveguide array must be designed and optimized specifically. We show here that networks based on coupled cavities in Photonic Chrystals (PhC) that are attracting growing interest because they constitute building blocks in many classical and quantum computing or information protocols, are particularly suited for this optimization

2 The PhC coupled cavity array

For zero-mode to exist, at least three coupled cavities are required. We have chosen the so-called L3 cavities, the most studied in photonic crystal. They are obtained by the omission of three consecutive holes on a line. Thus, our system is a minimal and simplest one and consists of three InP-based coupled PhC L3 cavities containing quantum wells as an active medium. The coupling between the cavities plays an important role for the observation of the zero-mode; its control is possible thanks to the barrier engineering technique [3]. This technique allows a large tuning of the evanescent coupling strength without changing the inter-cavity distance. We call photonic barrier the central row of air holes between two cavities. The modification of the radius of these holes results in changing the coupling strength. We define in our system two different sublattices, the first one is formed by the two extreme cavities while the second one being the middle cavity. Thus, as in any realization of 1D arrays, the system suffer from terminations in the chain since the extreme cavities do not "see" the same electromagnetic environment compared to the inner cavities, making their resonant frequencies slightly different.

3 The barrier Image approach

The presence of the photonic barrier leads to a cavity frequency modification. As the middle cavity is surrounded by two barriers, its frequency is detuned twice compared to extreme ones which see only one barrier. Therefore, the two sublattices become frequency-detuned, breaking the particle-hole symmetry that warrants the non-Hermitian zero mode. In our recent work [2], non-Hermitian zero modes have been observed in this three nanocavity array, but such a demonstration was limited to a very narrow coupling range because of the barrier-induced detuning.
The aim of the present work is to overcome this limitation by introducing what we call barrier images.
By systematically copying opposite barriers, all the cavities get surrounded by nearly the same environment, which makes their resonant frequencies approximately identical.

4 Experimental results

To experimentally validate this hypothesis, we fabricated a sample containing three coupled cavities with image barriers. The fabrication method consists in drawing the patterns on an epitaxial wafer of InP containing a stack

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of QWs, using electronic lithography followed by ICP (Inductively-coupled-plasma) etching. Finally, a dry plasma etching allows us to obtain suspended membranes. Photoluminescence experiments were performed to measure the emission spectra of the cavities. Fig. 1 presents a SEM image of a sample with image barriers.

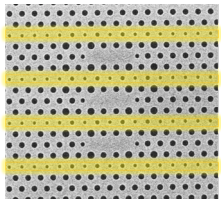

Fig. 1. SEM image of a PhC with three coupled L3. The barriers between cavities and image barriers are highlighted in yellow.

The sample is pumped using a pulsed (~100ps pulse duration) laser at 980nm, then the emission of the cavities is collected by a 100x, N.A.=0.95 microscope objective and sent to a spectrometer coupled to an IR sensor. The first experiment was carried out on a sample where the barriers are identical. It consists in localized pump at selected spatial region along a vertical axis crossing the three cavities. Results are shown in Figure 2.a where we plotted the emission intensity (color scale) as a function of the wavelength (x-axis) and the spatial position (y-axis). Here we can distinguish three different modes. The central mode has two maxima when pumping the extreme cavities. On the other hand, this mode features a far-field intensity node at the center and its near field is more intense in the two extreme cavities (see Figure 2.a). According to [2] this is a signature of non-Hermitian zero-mode. Explicitly, the $\pi/2$ phase jump between neighbor cavities which is interpreted as a π phase difference between the two extreme cavities, leading to an anti-symmetric-like far-field profile. In our previous work this observation was restricted to a small coupling range because of the sublattice detuning.

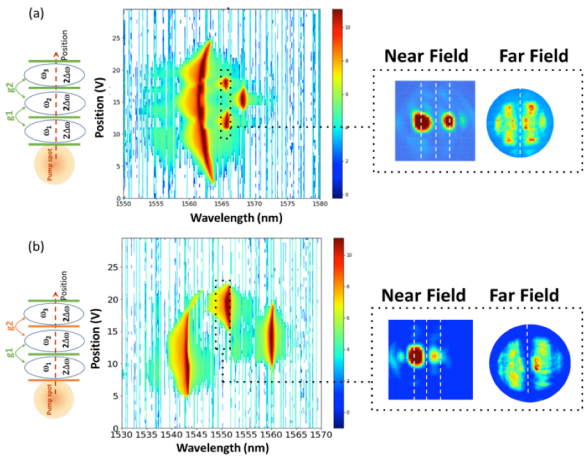

Fig. 2. Experimental results (middle) showing spectral intensity maps upon spatial scanning of a pump spot across the cavities as shown schematically on the left side. The corresponding near & far field images are present on the right side. (a) symmetric system where the barriers are identical (b) asymmetric-coupling system where the barriers are different.

Thanks to barrier-images the sublattice detuning issue is fixed and NH zero-mode observation is widely extended to large coupling range. This allows to further test the robustness of the zero-mode against coupling disorder by performing an additional experiment. It consists in deliberately introduce an asymmetry by choosing different hole radius for each barrier. This results in different coupling strengths between adjacent cavities. The central mode M2 in Figure 2.b shows the same features as the one in Figure 2.a i-e. anti-symmetric-like mode profile with the sole difference that the intensity distribution in the extreme cavities is asymmetric. This demonstrates the robustness of the zero-mode against coupling perturbation.

4 Conclusions

In conclusion, we have experimentally analyzed the existence of the zero-mode in a linear network of three coupled cavities designed in a Photonic Crystal platform. To cope with the usual problem of linear networks where the extreme cavities fill a different electromagnetic field than the inner ones, we propose barrier image approach. Our method symmetrizes the whole system and enables the inter-cavity coupling control without a concomitant frequency detuning. As a consequence a large widening of the coupling range where the zero-mode is observable is demonstrated. In addition, the robustness of the zero-mode has been demonstrated against coupling asymmetry in the system.

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