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Mesoscopic optics in coupled microcavities

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Abstract. Deformed microdisc cavities possess versatile application potential ranging from microlasers to sensors. Here, we investigate arrays of several coupled microcavity resonators. The coupling interaction between the cavities induces a wide range of features that sensitively depend on, and therefore can be controlled via, the intercavity distance. We use semiclassical methods from mesoscopic optics to characterise the system and its dynamics in real and phase space using Husimi functions. Our findings can inspire novel optical devices such as supersensors or novel light sources.

1 Introduction

The field of mesoscopic physics merges the classical and wave optical description with ray-wave correspondence being a paradigmatic principle and well-established concept. Its focus is on phenomena occurring at structures of medium scales, typically ranging on several 10s of micrometres corresponding to a few wavelengths fitting into the optical system. This scale range is of particular scientific interest since it allows one to develop numerically efficient theoretical approaches such as ray-based semiclassical methods for the modelling of integrated macroscopic devices with reasonable numerical effort ensuring not least sustainability. These models can be linked nicely to the models applied for classical optical systems engineering leading to functional and operational systems for specific applications [1], [2].

At the same time, mesoscopic optics addresses feature sizes which are readily accessible to practical realization. This, in turn, allows for the demonstration of applications with state-of-the-art technological effort established in micro- and nano-integrated device fabrication. It is the basis for direct transfer of simulation data into proof-of-principle devices and application schemes.

2 Discussion

We illustrate the potential of mesoscopic optics for a system of coupled deformed microcavities of Limaçon shape. In polar coordinates, the cavity radius R(φ) reads $R(\varphi) = R_0 (1 + \varepsilon \cos \varphi)$ with the deformation parameter ε set to 0.4 [2]. Figure 1 shows a typical mode in an array of three Limaçon cavities with their mirror symmetry axes aligned vertically.

The sensitive dependence of the system properties in the distance D between the cavities can be seen in Fig. 2 in terms of the far-field emission characteristics. While for large spacings (Fig. 2, right panel) the Limaçon characteristics [2] is clearly visible, the emission can change drastically for smaller spacings and strong coupling (Fig. 2, left panel) as reported in [1]. In particular, a complete reversal of the typical emission direction is possible, as well as superdirectional emission exceeding the values reached based on an array factor model applicable for larger spacings in the weak coupling regime.

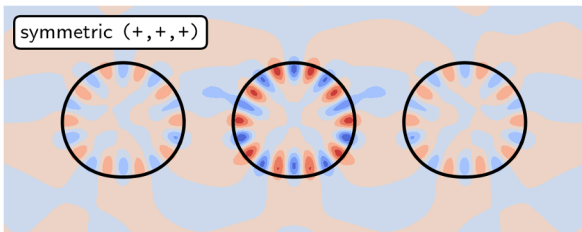

Fig. 1. Example of a symmetric coupled mode with wavenumber $nkR = 13.81$ in an array of three Limaçon cavities with refractive index $n = 3$. Antisymmetric modes exhibit a vertical nodal line in the intracavity space.

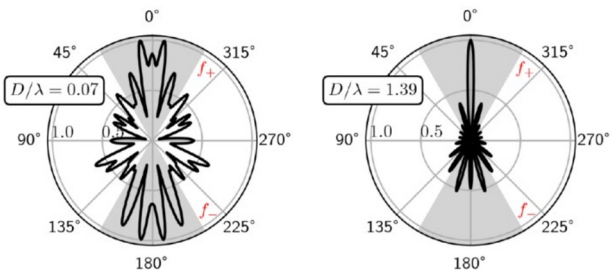

Fig. 2. Sensitive dependence of the far-field emission on the intercavity distance D measured in terms of the wavelength $\lambda = 2\pi/k$ for the symmetric mode in Fig. 1.

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Concerning the characterisation of the coupling mechanism, we use semiclassical methods such as Husimi functions [3] to gain further insight. This is illustrated in Fig. 4, and we refer the reader to [4] for details on this powerful semiclassical method.

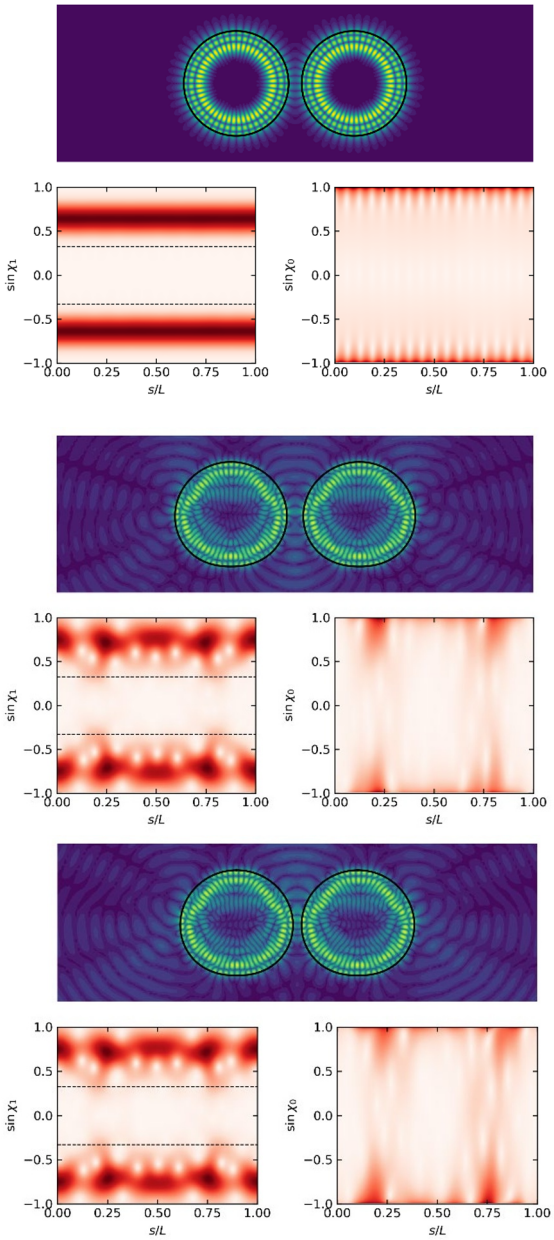

Fig. 3. Resonance patterns (top panels) and incoming (left panels) and outgoing (right panels) Husimi functions at the left cavity for three different systems of two coupled microcavities (shown are the intensity roots). First, two weakly coupled disks define the reference case. Second (third), two moderately (strongly) coupled Limaçons cavities are shown. Notice how the different coupling strength influences the intracavity wave patterns, the resulting emission characteristics, and the outgoing Husimi functions. Here, s/L is the normalized arc length measured from 12 o'clock ccw, χ is the angle of incidence.

An efficient method to characterise the coupling strength is to use the resonance splitting as a measure. This is shown in Fig. 3 for the case of two coupled Limaçon cavities while rotating their mutual orientation.

We find that the coupling strength depends on the cavity orientation angle θ for the situation of a resonance with a somewhat triangular shape considered here. It is strong in the situation marked by 2 in Fig. 3, when the cavities are orientated such that high intensity "corners" of the resonances are close to each other. This is not the case in situation 1, and accordingly the coupling and the resonance splitting are smaller. The existence of three oscillation loops in Fig. 3 agrees with the triangular resonance morphology.

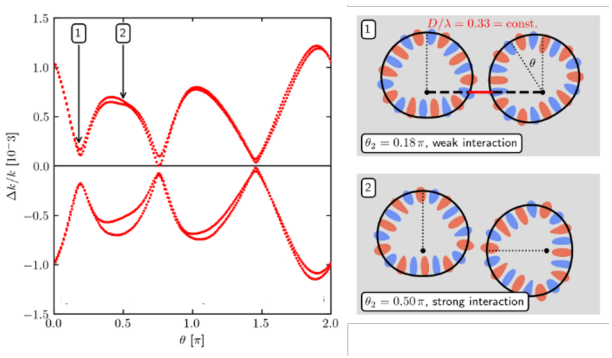

Fig. 3. Left: Resonance mode splitting for two Limaçon cavities as a function of the orientation angle θ. The intercavity distance D is measured along the coordinate centres marked by dots The splitting and thus the coupling strength depend on the relative orientation of the cavities and can be related to the inherent resonance morphology as shown in the right panels.

3 Conclusion

Mesoscopic systems cover a broad range of devices and phenomena ranging from optical microcavity systems to electronic devices such as Dirac fermion optics in graphene systems [5]. Besides the coupling of microcavites, the presence of sources in another, related topic of interest closely related to coupling [6] and a tool to manipulate the system properties.

We showed that light in optical systems on the mesoscopic, typically micrometer scale, can be versatilely controlled and tamed resulting in tailored emission characteristics or sensing properties.

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