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Coherent control of scattering and absorption in organic microresonators

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Abstract. We study coherent perfect absorption in organic microcavity resonators and extend these principles and our findings to more complex microresonator systems that, beyond absorption, also possess additional cavity energy dissipation mechanisms. The experimental approach uses laser interferometry to closely monitor the energy fluxes within the system at all device ports as a function of the device geometry and the phase relationships of the incident beams. A particular focus is on optical systems based on 2nd order Bragg gratings, which are crucial for the operation of organic distributed feedback (DFB) lasers or as light incouplers in optical waveguiding films. Coherent control allows the diffraction efficiency of the underlying grating to be tuned over a wide range of values. This strategy allows significant optimisation of resonator structures for high efficiency light coupling in optical waveguides and fine tuning of grating parameters for the most efficient optical mode conversion.

The ability to manipulate a light beam in a specific way, including controlling its directionality, localising the optical wave within the resonator or managing the light-matter interaction, is a key feature of any engineered optical system. Due to technological advances, recent research has extensively explored various microresonators with different geometries, efficiently managed by careful device design and coherent optical control. These studies have emphasised the importance of coherent control and critical coupling, highlighting the potential of tailored light-matter interactions to enhance device performance across a spectrum of applications [1, 2]. Interferometric measurements here play a crucial role in the experimental characterisation and understanding of the resonant properties of various microcavity devices and the effects of energy dissipation on them.

Figure 1 schematically illustrates the mechanisms of coherent perfect absorption (CPA) in a planar microcavity (a-c) and coherent perfect diffraction in a second-order distributed feedback (DFB) structure (d-f). In the context of the planar microcavity resonator operating as a two-port system, achieving CPA requires precise adjustment of the intracavity absorption and optimization of the reflectivities of both mirrors [3]. This is illustrated in Fig. 1c), where coherent control can lead to perfect absorption or enhanced transmission (not shown) by manipulating the intensity and phase relationships of two counterpropagating beams [3].

In contrast, the second-order distributed feedback structure operates as a four-port device. Coherent control is used not only to modify the transmission characteristics of the device along the propagation direction of the incident beams, but also to adjust the diffraction process of the underlying second-order Bragg grating. With a properly designed diffraction efficiency for the underlying grating and an appropriately selected waveguide, the diffraction efficiency can be coherently controlled and finely tuned. In this device, it is possible to achieve a coherent perfect transmission regime, where all incident optical power is effectively transmitted, resulting in virtually zero diffraction efficiency of the underlying grating. On the other hand, the device can be tuned to exhibit coherent perfect diffraction with a diffraction efficiency close to 100%.

In this study, we explore organic microcavities and second-order Bragg grating light incouplers as exemplary systems to demonstrate coherent control of light scattering and absorption in some basic microresonators. Coherent control is achieved using a modified Mach-Zehnder interferometer setup tailored to precisely monitor all leakage fields emitted from both two-port and four-port microresonator devices. Our microcavities consist of C_{60} organic thin films of various thicknesses sandwiched between two SiO_2/TiO_2 dielectric mirrors. The structure is carefully optimised by transfer matrix simulations to operate close to the coherent perfect absorption regime [3]. This refined design is then used as the basis for four-port devices in which the absorption process in a standard microcavity resonator is replaced by coherent light scattering into the fundamental optical mode of the waveguide film.

As a prototype of such a device, we use a laser-inscribed 2nd order Bragg grating in the TiO2 waveguide layer on a glass substrate. The parameters of the structure are further optimised using finite-difference time-domain (FDTD) techniques to fine-tune the performance of the de-

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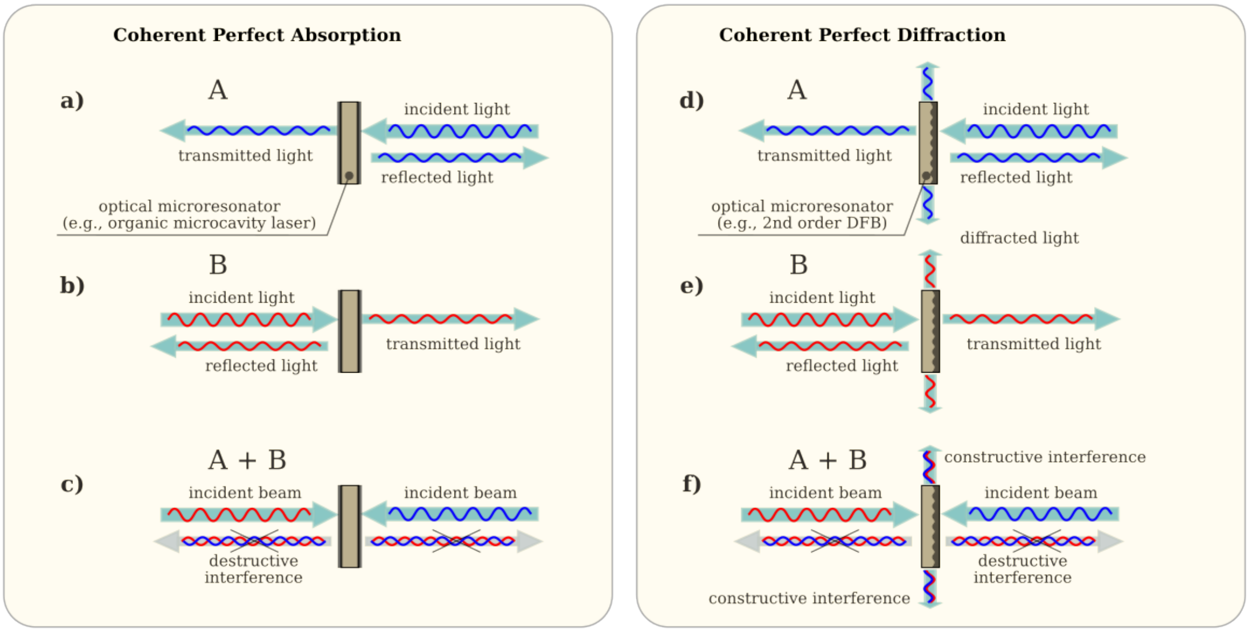

Figure 1. Illustration of coherent perfect absorption (CPA) (a-c) and coherent perfect diffraction (d-f) in a planar microcavity and a second-order distributed feedback (DFB) structure, respectively. Two extreme cases of coherent perfect absorption and coherent perfect diffraction in a planar microcavity (c) and a second-order DFB structure (f) are schematically shown.

vice. This involves optimising not only the waveguide and diffraction properties of the underlying grating, but also the lateral design of the entire device, which is finite and must precisely match the geometry of the pump beams. Experimentally, we show that the diffraction efficiency of such a four-port system, an inherent property and feature of any diffractive device, can be varied over a wide range of values by coherent control. Finally, we discuss various approaches and interferometric device designs that allow effective control of light direction and propagation.

In summary, our results provide insight into how coherent excitation can be used to achieve specific wave manipulation outcomes — from perfect coherent absorption to perfect coherent diffraction. This can be achieved not only in two-port devices, but also in multi-port devices, where energy is transferred from one coherent mode to the other through the diffraction process. The efficiency of this process can be tuned over a wide range of values. Although the approach is currently used in the linear regime, it facilitates efficient optical mode conversion between different resonances in coupled organic resonator systems [4], which can be crucial for integrated on-chip technologies and applications. All the findings can be easily transferred and applied to one-port devices, which are more practical, with little degradation in performance.

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