Directional Emission from Chaotic Microdisk Lasers and the Role of Boundary Imperfections

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Abstract— Optical microdisk laser provide a promising alternative to the well-known Fabry-Perot lasers as well as to VCSELs as the size of optical devices is further reduced to the scale of few micrometers. Whereas high Q-modes are available through whispering-gallery-type resonances that are trapped by total internal reflection inside the resonator, it remains a challenge to achieve directional emission by suitably breaking the rotational symmetry of the devices. In a previous work (J. Wiersig and M. Hentschel, *Phys. Rev. Lett.*, Vol. 100, 033901, 2008.) [6] we have shown that the so-called Limaçon-shape provides a robust possibility to combine directional far-field emission with high Q-factors. In detail, the far-field characteristic is determined by the unstable manifold of the cavity, a quantity well-known in the field of dynamical systems and quantum chaos. It implies that ray-based calculations, wave-simulations and experiments yield practically the same result. In particular, the easy-to-implement ray-optics methods are an appropriate tool to predict the far-field of microdisk lasers. A long-standing problem is to understand the role of boundary imperfections. Presumably these are responsible for the reduction of the Q-factors observed in experiments in comparison to the theoretical predictions. Here, we consider exemplarily the reflection of a Gaussian beam at a surface that was equipped with sharp and rounded cusps of wavelength size. We find that this changes the properties of the reflected beam considerably. We conclude that in practice, such imperfections will reduce the cavity Q-factors and will influence the far-field emission properties of microdisk lasers.

1. INTRODUCTION

The ongoing miniaturisation of photonic devices calls for new devices that provide lasing properties on the microscale. Besides the well established vertical-cavity surface-emitting lasers (VCSELs), optical microcavities [1–3] and microdisk lasers provide the unique possibility to combine ultrahigh Q-factors and directional emission characteristics in the far field. In contrast to the well-known Fabry-Perot-scheme based lasers where light is confined travelling back and forth between two mirrors, light confinement in optical microcavities is achieved using total internal reflection of light at the cavity boundary. For angles of incidence larger than the critical angle χ_c for total internal reflection, ray optics ensures that no light will leave the cavity, whereas in wave optics there remains a small evanescent leakage (tunneling). It still allows for the desired high Q-factors that are realized, for example, through the whispering gallery modes in circular microdisk cavities. However, their rotational invariance does not allow for a preferred direction of far-field emission that would be a prerequisite for every laser concept. There are many concepts how to overcome this difficulty ranging from composite systems via the use of resonance crossings [4] to specially designed geometries, see Ref. [5] for a summary on this subject.

2. ROBUST UNIDIRECTIONAL FAR-FIELD LIGHT EMISSION FROM LIMAÇON-SHAPED MICROCAVITIES

One particularly successful microdisk shape that was theoretically predicted to possess directional emission properties is the Limaçon-geometry [6]. It reads in polar coordinates (r, ϕ): $r(\phi) = R_0(1 + \epsilon \cos\phi)$ with mean radius R_0 and a geometry parameter ϵ describing the deviation from the rotationally invariant circular shape, values around $\epsilon = 0.43$ yield the best directionality. This prediction was confirmed by four different experimental groups within one year [7–11].

In Figs. 1 and 2 examples of resonances in a Limaçon-shaped cavitiy are shown for two different quality factors Q, for a rather low one on top, and a higher one in the bottom rows. The refractive index of the cavity is assumed to be $n = 3.3$ corresponding to the typical case of microdisks made of semiconductor heterostructures placed in air with refractive index $n_0 = 1$. The critical angle is related to the refractive index via $\chi_c = \arcsin(1/n)$ The geometry parameter was chosen as $\epsilon = 0.43$. Although this parameter was found to optimize the directionality in light output, other ϵ

yield comparable output chracteristics [11]. The two possible polarizations of light are considered, namely TM polarization (transverse magnetic case, Fig. 1), and TE polarization (transverse electric, the case with the Brewster angle feature, Fig. 1). TE polarization yields, in general, better results in

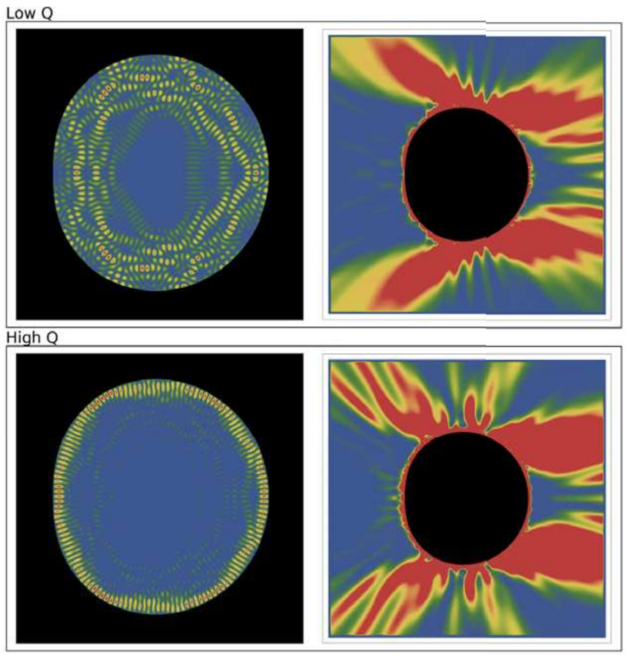

Figure 1: Resonances of TM type in the Limaçon-shaped microcavity with $n = 3.3$ and $\epsilon = 0.43$. Shown are $|E_z|$ (with E_z the electric field component perpendicular to the resonator plane) and the total intensity in the left and right panels, respectively. The mode's vacuum wavenumber k is given by $\mathrm{Re}[kR_0] = 21.0866$ and the quality factor $Q = 8978$ in the upper row, and $\mathrm{Re}[kR_0] = 22.1895$ and $Q = 18584$ in the lower row. The cavity wavelength is $\lambda_c = 2\pi/(nk)$. The Q-factor is obtained as $Q = \mathrm{Re}[kR_0]/(-2\,\mathrm{Im}[kR_0])$. Remarkably, the far-field pattern is practically independent from the resonance chosen.

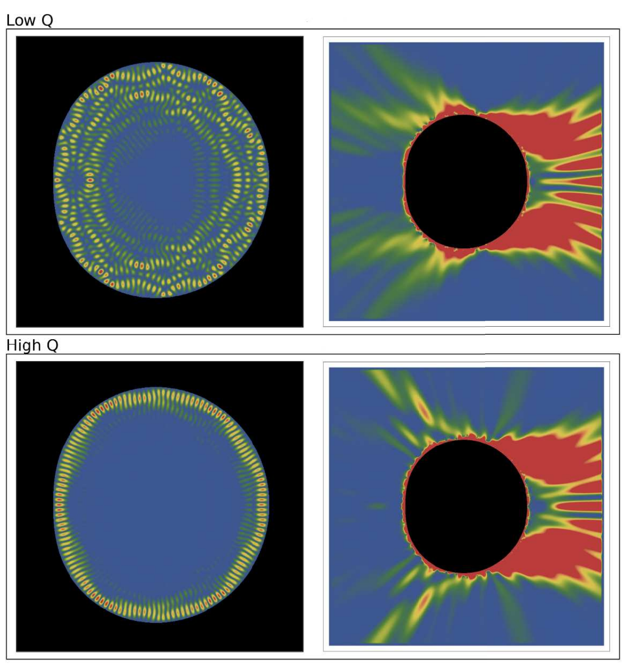

Figure 2: As before, but for resonances of TE type and the magnetic field component $|H_z|$ shown in left panels. The wavenumbers and Q-factors are $\mathrm{Re}[kR_0] = 20.6808$ and $Q = 14878$ for the upper row, and $\mathrm{Re}[kR_0] = 21.8779$ and $Q = 85012$ for the lower row. The better unidirectionality in the far-field characteristic of TE polarized modes in comparison to the TM case is clearly visible.

terms of unidirectionality than the TM case. The resonances and wave patterns inside (left column) and outside (right column) the resonator were obtained using the freely available simulation package MEEP [12]. The whispering-gallery-type character of the resonances is clearly visible especially for the cases of the higher Q-factors. For the examples with lower Q-factor in the top row, the chaotic character of the cavity becomes evident in form of deviations from the regular pattern of typical whispering gallery modes realized in rotationally invariant geometries. Notice that the rotational symmetry is broken in the Limaçon-case for all $\epsilon > 0$.

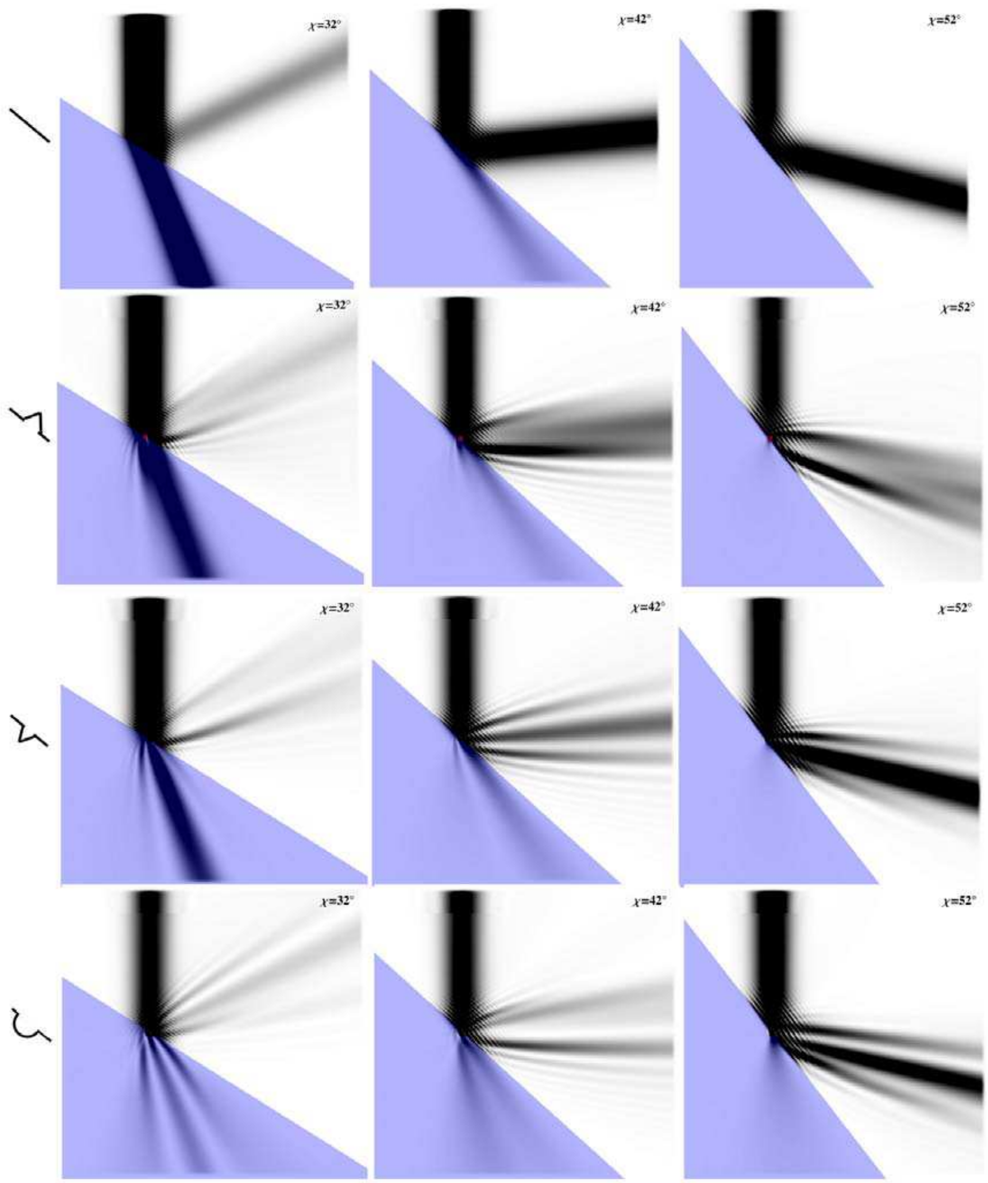

Figure 3: Role of surface roughness as function of the angle of incidence. A Gaussian beam in air is approaching an interface of refractive index $n = 2/3$ (corresponding to the reflection at a glass-air interface). The critical angle is 42°, see the central column. Subcritical incidence of 32° is depicted in the left, supercritical incidence of 52° in the right column, all for TM polarized light. The typical defect size is of the order of the wavelength λ of the material with the larger n, the beam waist of the Gaussian beam is chosen as 5λ. The upper row shows reflection at a planar interface for reference, the defect structures considered in the lower three rows are shown on the far left. The distortion of the reflected light is clearly visible. It depends, as expected, on the particular realization of the defect and amounts to a substantial broadening of the reflected beam and a substantial and varying intensity distortion of the originally Gaussian beam profile.

Remarkably, we find very robust and universal far-field emission characteristics that do not depend on the particular resonance chosen. The reason for this is that the emission characteristics of the cavity is determined by the so-called unstable manifold [6, 13]. This quantity is well known in the field of nonlinear dynamics and a characteristic of the phase-space of the corresponding ray-optical billiard, see, e.g., Ref. [6] for details. In this context we point out that ray simulations yield, therefore, very nice agreement with wave simulations [6, 11] and experiments [10]. This is remarkable because the wave simulations are not at all performed in the ray limit, and the size parameter realized in the experiments is yet in another regime. The agreement of all three data sets underlines the robustness of the proposed scheme against geometry imperfections and with respect to the mode chosen for the lasing operation.

We draw the reader's attention also to a characteristic difference between the far-field patterns of TM and TE polarized modes. It has its origin in the Brewster angle feature in the reflection coefficient important for TE polarized light. As a consequence, TE polarized light shows a better unidirectionality in the far-field, see Fig. 2, because extra emission directions (towards the left side) present for TM polarized light, Fig. 1, are missing.

3. ROLE OF SURFACE ROUGHNESS

Whereas the nice agreement between ray and wave simulation and the experiments allows one to use the straightforward and numerically cheap concept of ray simulations to determine the far-field emission characteristics of chaotic microcavity lasers, there are differences between theoretical calculations and experimental results when one looks on the Q-factors of the individual resonances. In general, the theoretically determined Q-factors can be considerably larger than the experimentally found values [11]. Boundary imperfections present in the experimental realization of optical microcavities are expected to be one important issue here.

This provides the motivation for our studies on the role of boundary imperfections. In order to concentrate on the boundary effect and avoid the influence of resonance-specific properties, our starting point is the reflection of a Gaussian beam at interfaces where different boundary defects are realized. The results of this numerical investigation are summerized in Fig. 3. We studied different kinds of wavelength-size boundary defects, in the form of sharp and rounded cusps, for subcritical, critical, and supercritical incidence of a Gaussian beam. For comparison, reflection at a perfect, planar interface is shown in the upper row. Near critical incidence, semiclassical corrections to ray optics lead to additional effects [14–18] that we, however, do not discuss here.

The effect of surface roughness is a general broadening of the reflected beam that can explain the reduction of the Q-factors observed in experiments. The details of this process in the case of resonance modes, and the role of interface curvature, will be the subject of a future work.

4. CONCLUSION

In conclusion, we have shown that the issue of achieving directional emission from microdisk lasers can be solved. We have introduced the Limaçon shape as a chaotic microcavity device that allows one to combine ultrahigh Q-factors and unidirectional output characteristics in a robust and universal scheme. This universality can be explained and understood using the concept of the unstable manifold.

The presence of boundary imperfections is argued to be one reason that reduces the Q-factor of resonant modes in experiments. In numerical simulations of the reflection of a Gaussian beam, a considerable broadening and distortion of the reflected light beam is observed and identified as a possible source for the reduced Q-factors observed in real devices.

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