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Optimization of prism coupling to high-Q modes in a microsphere resonator using a near-field probe

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Abstract

In this paper, we demonstrate a novel method for optimizing the in- and out-coupling of light confined in the fundamental high-Q whispering-gallery mode of a microsphere resonator via an external prism coupler. The technique relies on the use of a near-field probe to map the modes of the resonator and to obtain topographical information at the same time. We demonstrate the feasibility and efficiency of this technique by applying it to a sphere with a radius of 59 μm.

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1. Introduction

High-Q Mie resonances in dielectric microspheres, the so-called whispering-gallery modes (WGMs), have been subject of intense research in the last decades [1–3]. WGMs are a special family of eigenmodes of a spherical (or cylindrical) cavity of radius r and refractive index N [4]. The resonances occur at discrete values of the size parameter $x = 2\pi r/\lambda$, and can be described by their polarization and a set of three mode numbers: a radial number or order number n, giving the number of intensity maxima in the radial dependence of the mode, an angular mode number l and an azimuthal mode number m, which can take the values $m = -l, -l + 1, \ldots, l - 1, l$. The mode numbers l and m are similar to the quantum numbers

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describing the angular momentum of the electron in a hydrogen atom. Of particular interest are WGMs which have $l \simeq m$ and $n = 1$. In a geometrical optics picture, these modes can be described as rays bouncing off the internal surface of the sphere by total internal reflection. Their strong confinement and large quality factor make them ideal candidates for realizing devices such as low-threshold lasers [3,5,6], integrated optical devices [7,8] and high resolution accelerometers [9]. Moreover, these modes have a small mode volume and thus a high electric field per photon. This is an essential ingredient to observe cavity quantum electrodynamical (QED) effects [10], or to study the interaction of the modes with individual atoms [11,12]. The mode with $n = 1$ and $m = l$, the so-called fundamental whispering-gallery mode (FWGM), provides the smallest mode volume of all WGMs.

In a controlled experiment, it is desirable to be able to optimize the coupling of light to a single WGM, e.g., the fundamental mode, in a routine and efficient manner. This allows on one hand to investigate non-linear effects at extremely low pump powers, as all pump light is tunneled into a single highly confined mode. On the other hand, in experiments aiming at coupling of single quantum emitters to a single mode of an optical cavity all photons in that particular mode should be coupled out with highest efficiency.

One main obstacle of spherical resonators (microspheres as well as microdiscs or toroids) compared to, e.g., Fabry–Perot-type cavities is that there is no preferred direction into or out of which light can be coupled. Nevertheless, different methods have been developed to couple light to WGMs in spherical resonators. External couplers made from tapered fibers [13,14] as well as frustrated total internal reflection at a prism surface [15] or at angle polished fibers [16] have been used successfully. Also directional emission from nearly spherical resonators was demonstrated [17]. The theory of prism coupling to WGMs in spherical resonators was analyzed in detail in [18]. In our experiments, we use a prism coupler which is the most flexible device, as it provides an ability for fine adjustment by convenient manipulation of the incident free beams [18]. Also, it allows one to control the Q-factor of the WGM over several orders of magnitude by varying the distance between the microsphere and the prism surface. External couplers, mandatory for spherical resonators, have to be aligned actively with respect to the geometrical symmetry axis of the resonators. Due to the production process, which is usually a melting procedure, there is always a small ellipticity (of a few %) and thus a well defined symmetry axis. Mismatch of the spatial alignment with respect to this a priori unknown axis rapidly decreases the efficiency of coupling.

In this paper, we describe a novel method determining the symmetry axis of a slightly non-spherical microsphere resonator and, hence, optimizing the coupling of light to the FWGM when using a prism coupler. In our method, we simultaneously map the intensity distribution of WGMs on the sphere surface and the sphere's topography by using a near-field probe. For this purpose, techniques from scanning near-field optical microscopy (SNOM) [19] were employed. The principle of the mode mapping technique is that a very small, sub-wavelength, scatterer (an optical fiber tip) interacts with the evanescent part of the WGM. First, experiments utilizing this principle [20] aimed only at an identification of different WGMs via their spatial intensity distribution. In previous experiments, we improved this method by using an actively stabilized probe using the shear-force method [21]. The stabilization of the SNOM tip with respect to the sphere's surface provides topographical information which has not been used so far. Our approach is to use this information together with the optical information from the mode mapping to optimize the coupling of WGMs in nearly spherical to the prism.

2. Experimental

The experimental setup is sketched in Fig. 1. A microsphere of radius $r = 59$ μm is fabricated by melting a thin rod of Suprasil glass with a CO_2 laser [22]. The microsphere is mounted on a translation stage combined with a goniometer and a rotation stage. Before the experiments, the sphere is coarsely aligned with respect to the prism