Splitting of high-\(Q\) Mie modes induced by light backscattering in silica microspheres

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We have observed that very high-\(Q\) Mie resonances in silica microspheres are split into doublets. This splitting is attributed to internal backscattering that couples the two degenerate whispering-gallery modes propagating in opposite directions along the sphere equator. We have studied this doublet structure by high-resolution spectroscopy. Time-decay measurements have also been performed and show a beat note corresponding to the coupling rate between the clockwise and counterclockwise modes. A simple model of coupled oscillators describes our data well, and the backscattering efficiency that we measure is consistent with what is observed in optical fibers. © 1995 Optical Society of America

High-\(Q\) Mie resonances in spherical dielectric resonators, so-called whispering-gallery (WG) modes,\(^1\) have led to a wide range of activity in optics, starting with experiments on microdroplets by Ashkin and Dziedzic\(^2\) in the 1970’s. More recently, the combination of the strong confinement of the electromagnetic field in these modes and their long lifetime has attracted new interest in view of cavity quantum electrodynamics experiments dealing with a few tightly coupled atoms and photons.\(^3\) Along these lines, we have proposed and thoroughly analyzed an experiment that leads to the quantized deflection of an atomic beam grazing a WG mode.\(^4\) Highly confined and long-lived photon modes are also ideal for producing low-threshold laser effects in microspheres.\(^5,6\) Finally, high-\(Q\) WG modes may be used to realize quantum nondemolition measurements, as pointed out by Braginsky et al.\(^7\) We have observed that, for \(Q\) values above a few \(10^8\), each resonance is generally split into a doublet. We show here that this splitting is due to backscattering inside the sphere that couples the clockwise (CW) and counterclockwise (CCW) WG modes and lifts their degeneracy. A similar line-splitting effect was observed in a fiber-ring resonator in which large amounts of backscattering were artificially induced.\(^8\) In our microresonators a backscattering efficiency of \(10^{-10}\) per round trip is enough to split the resonances. The sensitivity of our experimental setup has allowed us to investigate fully this effect, which was only briefly mentioned in Ref. 9.

Our experimental setup is shown in Fig. 1. It is an improved version of the apparatus described in Ref. 10. We now operate in a vacuum-tight chamber where microspheres are produced and studied. We obtain reproducible silica resonators, 40–300 \(\mu m\) in diameter, by melting the end of a fiber with two counterpropagating CO\(_2\) laser beams. At a pressure of approximately \(2 \times 10^{-6}\) mbars, spheres can be kept for several weeks without degradation. Efficient coupling to high-\(Q\) strongly confined WG modes is achieved with a high-index prism, through frustrated total internal reflection. The beam of a diode laser stabilized on a grating and a Fabry-Perot cavity (linewidth 50 kHz) is coupled into the sphere by tunneling of the evanescent field across the piezo-controlled gap between the prism and the sphere (resolution 2 nm). The power coupled into a mode is in the 100-nW range at critical coupling. We detect resonances at the exit of the prism with a phase-modulation technique at 40 MHz, using an electro-optic crystal (EO) and a lock-in amplifier.\(^11\) When the laser frequency is scanned, each resonant WG mode gives rise to three lines 40 MHz apart, providing a convenient frequency scale. For \(Q\) values above a few \(10^8\), each line generally splits into a doublet. This is shown for one side component in Fig. 2(a); the splitting is \(\Delta \nu = 1\) MHz and the width (FWHM) is \(\nu = 270\) kHz, corresponding to a quality factor \(Q = 1.4 \times 10^9\). These measurements have been repeated on many different modes and spheres. Although the measured \(Q\)’s are always about the same for highly confined WG modes, their splittings range from 300 kHz up to a few megahertz. They are intrinsic properties of the modes, independent of the laser power.

WG modes are quasi-bound states of light with high angular momentum numbers \(l\) and \(m\) and low radial number \(n\). In perfect spheres, resonance frequencies do not depend on \(m\). However, our resonators have a typical \(10^{-3}\) eccentricity, which lifts the degeneracy between \(n\) and \(l\) modes with different \(|m|\)
The Rayleigh scatterers assumed in this model also radiate power outside the modes; this loss can be described by the Rayleigh extinction coefficient \( \alpha_s = (8\pi^3/3)(\rho_{sc}\alpha^2/\lambda^3) \). We calculate that this contributes to less than 10% of the observed \( Q \)'s. To account for the measured \( Q \) values, we incorporate into our model an imaginary part of the bulk material refractive index.

To test our coupled-oscillators model, we set up a beam splitter and a photomultiplier tube in order to detect backscattered light (see Fig. 1). When tuning the laser frequency, we observed resonant doublets on the backward light, at the same frequencies and with the same widths as in the forward direction (see Fig. 2). The imbalance of the two peaks can be explained simply by a small amount of parasitic light reflected back from the exit face of the prism that coupled directly to CCW modes. This changes the balance between the two modes and slightly distorts the shape of one of the resonant peaks. We observed that the backward resonant signal progressively disappears when the gap between the prism and the sphere is made smaller. This occurs because coupling to the prism broadens the resonance until its width becomes larger than the splitting. This is well described by our model, which requires a large splitting-to-width ratio for a sizable CCW field to be built up.

We have also performed time-decay measurements on our system. We use the lock-in amplifier dispersive signal to lock the diode laser, so that one sideband of the excitation field (approximately 5% of the total intensity) is on resonance. When the rf signal feeding the electro-optic phase modulator is switched off, the output light in the forward direction is the sum of the reflected excitation field (at the carrier frequency) and the field scattered by the sphere into the prism. The decay of the field amplitude in the sphere is then recovered by demodulation of the photodiode signal at 40 MHz. Figure 3 shows such a signal averaged over 20,000 runs. The laser sideband was locked at the center of the doublet to excite the two eigenmodes symmetrically. As expected, one observes a damped oscillation. The beat-note period \( T = 0.92 \mu s \) is related to the doublet splitting by the predicted relation \( T = 2/\Delta \nu \). To get enough signal, we reduced the sphere-prism gap so that the time decay of the field amplitude was only \( 2\tau = 0.51 \mu s \), where \( \tau \) is the photon lifetime. When the Fourier transform of the damped beat-note signal is performed, it nicely matches the doublet observed by continuous spectroscopy, as shown in the inset of Fig. 3.
Fig. 3. Time-decay signal with the laser sideband locked at the center of the doublet shown in the inset. The two eigenmodes are then equally excited and give rise to a beat note of period $T = 0.92 \mu s$ according to the fit shown by the smooth solid curve. To get enough signal, we decreased the prism–sphere gap, and the decay time was only $2\tau = 0.51 \mu s$. The measured beat-note period and the decay time agree well with the data obtained by continuous spectroscopy. This is clearly seen in the inset, where the Fourier transform of the temporal signal (dashed curve) is superimposed onto the experimental doublet.

one peak of a doublet gives a pure exponential decay with a time constant in good agreement with the resonance width.

All our experimental observations are well explained by our model for backscattering. Assuming mode volumes of the order of $1000 \mu m^3$, the range of splittings measured in our experiments corresponds to a backscattered intensity of approximately $10^{-10}$ per round trip. This is consistent with the backscattering efficiency and the Rayleigh attenuation of 2 dB/km measured in silica optical fibers.\(^{13}\) In both cases this phenomenological approach gives access only to the average ($\rho_\text{sc}$) and does not allow us to identify the nature of the scatterers. The mode splitting reported here results from the very features of microspheres that make them currently of interest, that is, strong confinement of light in long-lived modes. Among the possible applications of high-$Q$ microspheres, the backscattered field studied here can provide an elegant feedback source with which to optically lock a diode laser to a narrow sphere resonance and reduce its spectral width. We plan to use this method to obtain a compact and robust device with a fiber coupler that we recently developed.\(^{14}\)

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