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Optical Pulse Propagation via Whispering Gallery Modes in Glass Spheres

W. B. Whitten, R. W. Shaw, M. D. Barnes, and J. M. Ramsey

Chemical and Analytical Sciences Division

Oak Ridge National Laboratory

P.O. Box 2008 MS-6142

Oak Ridge, TN 37831-6142

Phn: 423/574-4882 Fax: 423/574-8363 email: shawrw@ornl.gov

ABSTRACT

Two-picosecond optical pulses were coupled into whispering gallery propagation modes of glass spheres. Applications of this technique to absorption spectroscopy are discussed.

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## Introduction

Early in this century, Rayleigh<sup>1</sup> showed that waves could propagate close to the wall of a spherical cavity with very little loss as long as the wavelength was small compared to the cavity circumference. The treatment was primarily for acoustic waves, modeling the whispering gallery effect, but he pointed out that electromagnetic waves should behave similarly. Study of the optical properties of dielectric spheres has received new interest with improvements in optical instrumentation and the emergence of new applications for high-Q resonators. It has recently been shown that optical pulses propagating in whispering gallery modes can be treated analogously to pulses in a fiber optic waveguide. Since the optical fields extend beyond the surface of the sphere, the sphere's environment could alter propagation properties such as cavity ringdown time. We describe here some time and frequency-domain measurements of picosecond pulses in glass spheres of millimeter dimension and discuss potential analytical applications.

## Experimental

Two-picosecond duration pulses near 920 nm were generated using a Kerr lens mode-locked titanium:sapphire laser. The pulse train repetition frequency was 76 MHz, and the average power was 1 watt. The pulses were focussed into a 30-mm equilateral prism (SF-18,  $n=1.722$ ) at near normal incidence such that the beam waist was positioned near the second prism face, where evanescent wave coupling to a glass sphere (BK-7,  $n=1.51$ ) occurred. The spheres were loosely mounted on an XYZ translation stage by seating them on the rim of a drill hole in the mount. This arrangement allowed the sphere to be brought into contact with the prism without the possibility for excessive forces. The majority of the laser pulse intensity did not couple into the sphere and continued through the prism, exiting as a specular beam. The portion of the beam that did couple travelled around the sphere equator, and subsequent to each round trip re-entered the prism and traveled to the prism exit face. The image beyond the prism was the specular spot and a horizontal streak of light, that exhibited low vertical divergence. A portion of the light streak was collected using a short focal length lens and imaged onto a fast photodiode (17 ps risetime). The photodiode signal was processed using a digital oscilloscope (6 GHz bandwidth) or a 10 KHz-21 GHz RF spectrum analyzer. Oscilloscope data were refined using a fast Fourier transform.

Glass spheres with 8, 10, and 26.25 mm diameters were examined. The 8 and 10 mm spheres were from Edmund Scientific (Barrington, NJ) and the 26 mm sphere was obtained from Applied Image, Inc. (Glasstec Division, Buffalo, NY). The sphere diameter tolerance was  $\pm 0.5 \mu\text{m}$ , and the sphericity was specified to be  $\lambda/2$ .

## Results and Discussion

In the near normal incidence geometry described above, the incidence angle at the prism/sphere coupling face resulted in total internal reflection. Only weak sphere coupling was observed until it was discovered that a film of glycerin at the coupling point facilitated transfer between the media. A drop of glycerin was applied, and the excess was removed using a lens tissue, leaving a thin film of fluid. When acceptable coupling was achieved a bright and distinct equatorial ring of light was observed at the sphere equator, and the time profile of the collected light assumed an oscillatory character.

Figure 1 shows time traces of the photodiode signal for the 26.25 mm sphere. The oscillations of Figure 1a have a period of 216 ps, corresponding to travel around the sphere circumference at the speed of light in BK-7. When the sphere was backed slightly away from the prism face, this oscillatory signal disappeared. The signal decays with a characteristic time of about 5 ns, corresponding to a resonance  $1 \times 10^6$  quality factor (Q). The optical pulse undergoes approximately 32 trips around the sphere circumference within the 13 ns time period between the laser pulses; this corresponds to a pathlength of 2.6 m for potential interaction with a surrounding medium or adsorbed material.

Fourier transformation of this data results in the spectrum of Figure 2a that exhibits only the 2.38 GHz resonance and weak contributions from the second and third harmonics. Small changes in the experimental geometry result in excitation of different sphere modes at different frequencies. Minor adjustment of the sphere position produced Figure 1b, that transformed as the spectrum of Figure 2b. In a ray optics picture, the light path in the sphere can be thought of as an inscribed polyhedron; for modes of higher order (fewer apices) the round trip path length is shorter, resulting in a higher oscillation frequency. The decay of the higher frequency mode was faster (1/e at 4.5 vs 4.8 ns), in agreement with the notion that the steeper incidence angles at the apices results in greater losses. Similar data were gathered for each of the sphere sizes. The frequencies observed were 7.92 (8 mm, 7.91 GHz calculated), 6.30 (10 mm, 6.33 GHz) and 2.38 GHz (26.25 mm, 2.41 GHz). Signal processing using the spectrum analyzer resulted in spectra similar to those calculated using the FFT.

The propagation modes excited here in any particular experiment are not singular. Higher time resolution traces can show multiple, near-degenerate modes. In some cases these mode combinations result in envelope modulation of the overall waveform, i.e., beating. Care must be exercised to avoid collection of the specular beam from the coupling prism; the primary frequency

is present and dominates the signal, but strong envelope modulation occurs. The character of the oscillating waveform can be slightly dependent on the operating wavelength.

### Conclusions and Future

Picosecond optical pulses were coupled into whispering gallery propagation modes of macroscopic glass spheres. The effects of coupling geometry, sphere diameter, laser wavelength, and laser repetition rate were examined. The detailed selection of particular sphere modes is presently beyond our control. Fiber optic, as opposed to prism, sphere coupling is currently under investigation. We are investigating the use of these spherical resonators as media for absorption spectroscopy via cavity ringdown methods<sup>2</sup>; optical absorption by species at the sphere surface will create loss during each round trip, yielding a shorter cavity decay time (lower Q), indicative of the absorption. Absorbing gases and adsorbed materials are sample candidates. A robust, sensitive detector would result from this approach in that the spherical cavity geometry is immune to misalignment.

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