Estimation of One Photon Average Electric Field Strength Confined in Silica Glass Microsphere

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Abstract: ***In this paper, we present measurement results for estimation of the average electric field strength of one photon confined in the single whispering-gallery-mode (WGM) within a micro-scale space in a silica glass microsphere. With the precise control of microsphere diameter, fiber taper size, and a distance between sphere surface and collecting fiber taper, we can obtain single 1550nm-WGM emission from erbium doped microsphere silica glass pumped by 980nm laser beam. Using Poynting's vector theory, which describes the relation between the intensity over the electric field strength of an electromagnetic wave in a given area, we calculated the average electric field of one photon confined in WGM at silica microsphere surface. Our measured results well agree with the theoretical value within the measurement uncertainty. The average one photon electric field strength plays important role in applications such as optical trapping and tweezers, biological and chemical sensors.***

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1. Introduction

Silica microspheres are perhaps the best available optical micro-cavity devices. In these microspheres, Whispering-gallery-modes (WGMs) form via total internal reflection along the curved boundary. The WGMs in silica glass microspheres are interesting research objects because of potential applications in the opto-mechanics, force spectroscopy, optical tweezers, filters and sensors [1-4]. Among the applications of WGMs in microspheres the optical sensors have been seen in different fields such as molecular physics, chemical, biological and medical applications [5, 6], which are directly depended upon the optical force and/or electrical dipoles on the microsphere surface. Apparently, as shown in [4] the changes (either the frequency centroid or its width) related to the electric field strengths of the light confined within the microspheres through its evanescent part, though not much experimental discussion on it has been seen. The average electric field strength of one photon, or therefore of photons, confined in a glass microsphere could be, however, estimated theoretically as shown in [7]. It is difficult to measure directly the mode parameters such as the average electric field strength of those confined photons, because there is no way for a probe to access into the mode spaces located nearly on the surface of the microsphere from inside of the sphere. There is, however, another way of measuring some physical features of evanescence wave by direct measurement of atom-field force and/or optical momentum [8]. This is also well known that for microsphere cavity, the whispering gallery comb-like modes are produced where tens or more of those modes with their distinctive labelling, located on the region about the surface of the sphere. In report [9], each single mode of those could be selected out by adjusting some parameters such as coupling distance. The distance from the optical collecting tip (opticalfiber taper) to the sphere surface is sub-wavelength scale, and it is also known experimentally and theoretically that up to 90% or more of power could be pulled out in this distance as shown in report [10].

In this work, we show an experiment for estimating the electric field strength of the light confined within a modal volume in a microsphere cavity. The microspheres are made from Erbium-doped silica glass and the comb-like modes are produced by side pumping with a 980 nm diode laser source. Individual single-mode emission at 1550nm-wavelength range is selected by a special collecting system where the geometrical parameters (cross-section, length etc.) of the fiber tip are precisely established. From the measured optical powers then the electric field strengths of each individual single-modes could be deduced through the known relationship between them in the Poynting's vector.

2. Experiment

It is the basis of the present experiment system that is grounded on the Poynting's vector theory which describes the relation between the intensity over the average electric field strength (and then the average power) of an electromagnetic wave going in and getting out a given area. The equation to describe this relation in transmission medium (in our experiment the medium is of glass) is expressed as follows [11]:

$$I = c/n_2 \times \varepsilon_0 \times E_x^2 = P/\pi R_{z,\,ave}^2 \qquad (1)$$

where I is the intensity with the unit watt/m^2 in the S. I. unit system; c is the light speed in vacuum; $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is vacuum permittivity; E_x is the average (root mean square)electric field strength of the evanescent field overlapping the probe and far from the sphere a distance x. This field strength is well-known as the gradient one and it could be seen in the following form [8]:

$$E_x = E_0 \times \exp\left[-\pi/\lambda . (n_2-1)^{1/2} . x\right] \quad (2)$$

where E_0 is the average strength at the sphere surface or at x = 0, n_2 is the refractive index of glass, λ is the wavelength. With the probe position adjusting system, the probe is adjusted to cross the evanescent zone in a direction almost in parallel to the tangential to the sphere at the total internal reflection (TIR) location [10].

The erbium-doped silica microsphere lasers has been fabricated from the core of commercial erbium doped fibers (EDF), where homogenous erbium-doped glass with known erbium concentration was obtained from a core part of EDF. The erbium concentration of 2500ppm in silica glass, and the diameters of the microsphere of 50µm are choice for obtaining optical comb-like spectra of WGMs. We used a 980 nm laser diode with output optical power up to 170mW in single-mode emission (SDLO-2564-170) for excitation of the Er-ions. The optical coupling to the spherical microcavity for pumping and for laser output extraction was performed with two different half-taper optical fibers made by the chemical etching method. The waist diameters of the half-taper were 1µm, and the angle of the taper tip was 0.72°.
The pump light at wavelength of 980 nm is coupling into the Er-doped silica microsphere and the 1550nm-emitted light is selected out via the collecting taper fibers at the coupling distance x. The coupling gap was adjusted by a system composed of a 3D micropositioner and a lead zirconate-titanate (PZT) piezoelectric stack AE0203D08F with accuracy of 10nm.

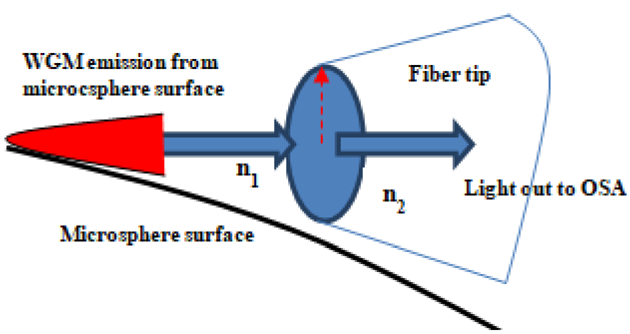

Figure 1: Schematic of WGM intensity collection through average $R_{z,\, ave}$ of fiber taper cross-section to the OSA.

The real setup described by equation (1) is illustrated in Fig.1, where the coupled light go through a round area of average radius $R_{z,\, ave}$ of the collecting taper fiber. The 1550 nm-collected light would then register to the Optical Spectrum Analyzer (OSA). The microsphere is fixed on a V-groove fixture for prevention of mechanical vibration. This setup can measure the power of the coupled light at specific distance that with a careful selection of experimental parameter such as the distance x, a single mode with a given wavelength is registered. The corresponding power of the measured mode is also obtained. Combination of the equation (1) and (2), the average electric field strength on the surface of the microsphere of the light and then of the single photon would be known after a correction of the power coupling in the sub-wavelength distances.

3. Results and Discussion

In order to demonstrate the performance of measuring method for determining the intensity of light confined within the optical microsphere, we conduct the measurement by first separating the targeted WGM with the steps similar to the steps done in our previous experiment [9]. The separated WGM is registered in the OSA where WGM's wavelength and average power are all obtained. Figure 2 presents comb-like WGM emission from microsphere cavity laser with coupling gap of 1.0+/- 0.05µm. We obtain 5 WGMs with optical power more than -20dBm and signal-noise-ratio (OSNR) more than 26dB which enough for one-photon electric field calculation.

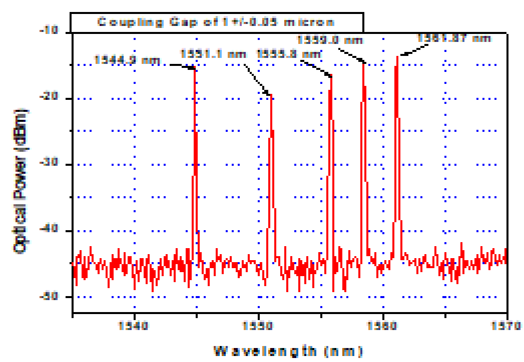

Figure 2: Spectra of comb-like WGM emission extracted from Er-doped silica micro cavity laser when the coupling gap between the taper fiber and the sphere surface of 1.0+/-0.05µm.

Experiment shows that a single mode of WGMs from microsphere cavity can be detected, when the coupling gap was less than 1.0µm. Figure 3 shows a spectrum of the single-lasing modes from the existing WGMs in the microsphere cavity, when the coupling gap was adjusted from 0.3 to 0.6µm with accuracy of 0.01µm. So in this mechanism of mode selection, only single mode could be considered and its electric field strength could be calculated separately. This way of detecting a single mode will avoid the disturbances of the dipole interaction between the collecting taper fibers with other WGMs which are not in consideration.

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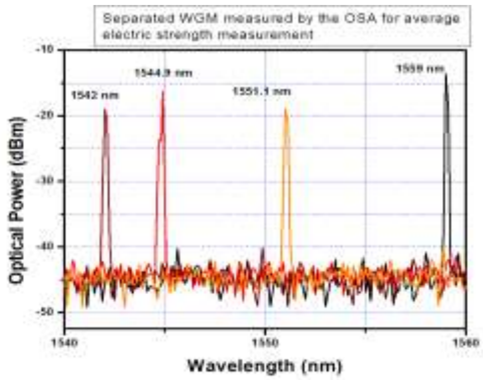

Figure 3: Spectra of single-lasing mode extracted from Er-doped silica microcavity laser when the coupling gap between the taper fiber and the sphere surface was 0.3µm (1559.0nm); 0.5µm (1551.1 nm); 0.55µm (1544.9 nm); and 0.6µm (1542.0 nm)

Numerical illustration for an average probe radius is $R_{z,\ ave}$ = 0.563µm with the waist radius r = 0.5µm, α = 0.72°. The spectral characteristics of the WGMs were analyzed by the optical spectrum analyzer Advantest Q8384 with a wavelength resolution of 0.01 nm. The obtained powers are then corrected by a corrective coefficients **C**. At the sub-micro measuring distances, the corrective coefficient **C** may go up to more than 90% [10]. The experimental measurement results with different **C** are listed in Table 1.

Table 1: Experiment data: measured E_x, electric field strength at surface E_0 and field per photon for mode given at diferent wavelength, distance and optical power

a) Corrective coefficient: C = 100%					
Wavelength (nm)	P (mW)	X (nm)	Ex (V/cm)	Eo (V/cm)	Eo, n (V/cm)
1559.0	0.04265	300	1680	5980.9	5.0
1551.1	0.01258	500	913	7654.1	6.4
1544.9	0.02344	550	1278	13384.8	11.0
1542.0	0.01258	600	913	11889.3	9.8
b) Corrective coefficient : C = 96%					
Wavelength (nm)	P (mW)	X (nm)	Ex (V/cm)	Eo (V/cm)	Eo, n (V/cm)
1559.0	0.04265	300	1715	6104.2	5.1
1551.1	0.01258	500	931	7812.0	6.5
1544.9	0.02344	550	1271	13314.9	11.0
1542.0	0.01258	600	931	12134.5	10.0
c) Corrective coefficient: C = 90%					
Wavelength (nm)	P (mW)	X (nm)	Ex (V/cm)	Eo (V/cm)	Eo, n (V/cm)
1559.0	0.04265	300	1771	6304.4	5.3
1551.1	0.01258	500	962	8068.2	6.7
1544.9	0.02344	550	1313	13751.5	11.3
1542.0	0.01258	600	962	12532.4	10.3

The average electrical strength of one photon confined into single WGM is of 8.2V/cm. The main distributions to the measurement errors are the measured powers and the measuring distances. As seen in the Table 1 (a, b, c), the average electric field strength of a photon is estimated with an error not greater than 5% within the corrective coefficients variance of 10% (i. e. within the power couplings from the microsphere to the collecting fiber is from C = 90% to C = 100%). In our present experiment, the PZT stage with the collecting fiber attached on it has an accuracy of around 10 nm. The total relative measurement errors are obtained by applying the law of error propagation [12]:

$$e^2 = e_1^2 + e_2^2$$

where e is the total relative error, e_1 is the relative error contributed by varying the coupling coefficient C, e_2 is the relative error of the measuring distances. These errors are listed in the Table 2.

Table 2: Errors of measurement of one photon electric field strength for modes of given wavelength, distance and optical power

Wavelength (nm)	P (mW)	X (nm)	e_1 (%)	e_2 (%)	e (%)
1559.0	0.04265	300	3.0	3.3	4.5
1551.1	0.01258	500	2.3	2.0	3.1
1544.9	0.02344	550	1.6	1.8	2.4
1542.0	0.01258	600	2.5	1.7	3.0

The theoretical average electric field strengths of one photon of the WGMs of wavelength at 1550nm-range confined in the silica glass microsphere cavity with radius of 50 microns may be all rounded to 8.6 V/cm by theoretical calculation [7]. The measurement given in Table 1 and 2 show a large variance of the average electric fields. The average one could be estimated and the total error now includes the average error due to each individual measurement as given in Table 2, and the scattering of the measured data. The average error of 3.3% is the error estimated from Table 2. The scatter error of 17.2% is estimated from data in Table 1, and the combined error is estimated about 17.6%. The deviation of the experimental to the theoretical one would be 0.4 V/cm or 4.9%. It is worthy to notice that the measured average electric field value of 8.2 V/cm is agreed with the theoretical one of 8.6V/cm within the experimental error.

The electric field strength of one photon plays a crucial role in a variety of optical systems [13, 14], especially for deposition of metallic nano-particles and/or trapping the semiconductor quantum dots (QDs) as qubits, with interactions mediated by the field of a microsphere cavity for sensing purpose [15]. In addition, the knowledge of electrical field of light may be useful for noble metal nanoparticle growth with different forms such as nanotrees and nanodendrites on the dielectric substrates by photo-induced methods for surface-enhanced Raman scattering probes [16], or even it will be useful in explaining the observation of two and/or three photon bound states [17] in nonlinear optic medium.

4. Conclusion

In conclusion, we presented the experimental results for measuring one photon average electric field of the 1550nm-light confined within a modal volume in a microsphere cavity. In our experiment, a single mode of WGM emission is selected out so that its measured power and wavelength are not affected by the other WGMs. The relative position between the microsphere and the collecting fiber is determined. The physical foundation of our experiment is based on the Poynting's vector equation. The average electric fields of one photon nearly on the surface of a microsphere are measured through the evanescence part of the field. The average one photon electric field of 8.2V/cm is estimated experimentally and this value is well agreeing the theoretical value within the experimental errors.

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