The experimental quest on dimension and material of microsphere for photonic jet microscopy

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Abstract. Our previous studies have shown the potential of applying photonic jet for microscopy. However, some parameters concerning the microsphere must be determined before practicing photonic jet for microscopy. This manuscript reports our quest for dimensions and materials of microsphere that fitted for on an optical microscope, experimentally. The main directive in our quest is the largest magnification or the best resolution of the image obtained by the microsphere. We find that if the refraction index ratio is getting larger or closer to two, it needs larger microspheres. On contrary, if the refraction index ratio is closer to one, it needs smaller microsphere.

1. Introduction

If a beam ($\lambda_0$) is propagating through a dielectric microsphere or micro-cylinder, it will be highly concentrated in the vicinity of the dielectric as non-evanescent beam that can propagate longer than the incidence wavelength ($\lambda_0$). This phenomenon is then known as photonic nano-jet [1] or photonic jet [2]. The highly concentrated beam possesses the resolution which can go beyond the diffraction limit which leads to the potential application in microscopy – as it was coined in 2004 [3], since the concentration is in the sub-diffraction-limit progressive beam [2,4].

For a practical use, a microsphere is laid on the top of the specimen at the microscope’s objective stage. The specimen and the microsphere are immersed in liquid [5,6]. The microscope might be operated in reflection mode as well as in transmission mode. As the photonic jet reaches the surface of the specimen below the dielectric medium, it will illuminate the specimen at high intensity and high resolution that can exceed diffraction limits [6]. We also have demonstrated the potential of photonic jet microscopy in free-space – without any immersion liquid [7], so we can use any biological object as the specimen. It also supported by numerical simulation [8]. However, there are some parameters must be considered to have the photonic jet microscopy effectively. The study on these parameters by numerical simulation concludes that the geometrical size (dimension) and the optical materials of microsphere [9] play the most important role in photonic jet microscopy.

Therefore, we have conducted some experiments in free space using an optical microscope, a stage micrometer and some soda-lime glass microspheres ($n_g = 1.5$) [7]; also some barium titanate microspheres ($n_{BT} = 1.9$). These experiments are our quests seeking the right microsphere for photonic jet microscopy in free space.
2. Experiment setup

Our optical microscope, stage micrometer and microspheres are arranged in a simplified scheme as in figure 1. The microspheres are placed directly on the stage microsphere; it makes the distance between them (δ) is considered as null. Soda-lime glass microspheres have a diameter, in average (D) of 40, 88 and 120 µm; whilst barium titanate, in average of 41, 80 and 94 µm. Lines on stage microsphere are observed and measured using the microscope (h). Their sizes, then, compared with the lines observed and measured under a microsphere (h'). The ratio between h' and h will yield, so called, the magnification of microsphere (Mex). These magnifications then plotted and evaluated. And, one of the evaluations is assessing experiment results by an optical geometric model.

![Figure 1. The experiment setup in free space using an optical microscope, a stage micrometer and transparent-dielectric microsphere. All the objective lens has the same numerical aperture of 0.75 with the magnification of 10×, 20× and 40×. The stage micrometer is placed as the observed object which has the length of 1 mm with 100 line division; it makes the smallest division of 10µm. The microspheres are made of soda-lime glass (ng = 1.5) and barium titanate (nBT = 1.9).](image)

3. Results and discussions

The data obtained are the width of lines on the stage micrometer before (h) and after (h’) magnified by the microsphere. An example of captured pictures with the width of line before and after magnified by a microsphere are presented in figure 2.

![Figure 2 An example of captured picture where data are obtained (a) h before and (b) h’ after magnified by a soda-lime glass microsphere, observed using a 40× objective lens.](image)

From these sizes the magnification of microspheres by experiment (Mex) are yielded as

\[ M_{ex} = \left| \frac{h'}{h} \right| \]
Plotting data yield a graphic of magnification as a variation of microsphere diameters shown in figure 3, whilst the magnification data ($M_{ex}$) are also presented in table 1. Figure 3 shows that larger barium titanate yields larger magnification; but smaller soda-lime glass yields smaller magnification. Larger magnifications can be obtained using larger microsphere for higher refractive index ratio, but smaller microsphere for smaller refractive index ratio.

![Figure 3](image.png)

**Figure 3** The experiment results: diameter of microsphere size varies image magnifications made by a microsphere

The largest magnification is yielded using barium titanate with a diameter of 94 µm. The refractive index ratio is a comparison of microsphere refractive index ($n_{µs}$) to the medium refractive index ($n_0$),

\[
\frac{n_r}{n_0} = \frac{n_{µs}}{n_0}
\]  

(2)

In our case, we have $n_{r,g} = 1.5$ for soda lime glass microsphere and $n_{r,BT} = 1.9$ for barium titanate microsphere. For evaluation, we use generalized magnification model of microsphere proposed in [6],

\[
M_{µs} = \frac{f_{µs}}{f_{µs} - R_{µs} - \delta}
\]  

(3)

With $f_{µs}$ as the focal point of microsphere,

\[
f_{µs} = \frac{h_{r} h_{r}}{\sin 2 \sin^{-1} \left( \frac{h_{r}}{R_{µs}} \right) - 2 \sin^{-1} \left( \frac{n_{0} h_{r}}{n_{1} R_{µs}} \right)}
\]  

(4)

So, from equation (1) and (3) we yield the magnification of microsphere as the results of experiment ($M_{ex}$) and optical geometric model ($M_{µs}$), as in table 1. Our experiment results in table 1 are distinct to the calculation using optical geometric model, especially for barium titanate (figure 4). As for soda lime
glass microsphere, the calculation is quite similar to the experiment results, especially for larger ones as we have reported [8]. Apparently, the refractive index ratio makes this distinctive result.

Table 1 Magnifications of microspheres as the results of experiment ($M_{ex}$) and optical geometric theory ($M_{µs}$)

| Microsphere            | $D$ (µm) | $M_{ex}$ | $M_{µs}$ |
|------------------------|----------|----------|----------|
| Soda-lime glass [7]    | 40       | 3.5      | 5.84     |
|                        | 88       | 3.3      | 3.30     |
|                        | 120      | 3.1      | 3.11     |
| Barium titanate        | 41       | 2.4      | 140.5    |
|                        | 80       | 3.7      | 41.3     |
|                        | 94       | 3.8      | 32.5     |

Figure 4. Experiment results compared to optical geometric theory [6] for (a) barium titanate microspheres and (b) soda lime glass microspheres
4. Conclusion
Our quests for dimension and material of microsphere for photonic jet microscopy have led to understanding of the practical use in free space that obtaining larger magnification is possible using barium titanate with a diameter around 80µm or larger. As for general practice, the refractive index ratio of microsphere to medium specifies the dimension of microsphere, whether small or large.

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