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Wavelength shift in microsphere lasers

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Abstract. The wavelength shift effect of the Whispering Gallery Mode (WGM) laser with Er^{3+}/Yb^{3+} co-doped phosphate glass microsphere has been investigated. The experiment was carried out by half fiber taper coupling technique. The microsphere lasers have been pumped at 980 nm to take full advantage of energy transfer effect from ion Ytterbium to ion Erbium. The WGM's wavelength shift were analyzed for sphere diameters of 90 μm. The observed lasing lines extends from 1532 nm to 1611 nm.
Keyworks: Microsphere, Whispering Gallery Modes, Lasers, Erbium Ytterbium co-doped phosphate glass.

1. Introduction

Rare earth-doped glass microspherical lasers are subject to numerous studies and significant progress has been achieved in the past decade. In the microsphere, the morphology-dependent resonance (MDR), so called Whispering Gallery Mode (WGM) - a particular mode of microcavity resonances - occurs when the fluorescent light travels in a dielectric medium along thin layer near equatorial. After repeated total internal reflections at the curved boundary the electromagnetic field can close on itself, giving rise to resonances and formed ”“whispering-gallery” waveguide modes. Inside the microsphere, the circulation of the ”whispering-gallery” modes provides the necessary path length for absorption, thus making it possible to reduce the laser threshold drastically. In order to couple light in or out of the microsphere, it is necessary to utilize overlapping of the evanescent radiation field of WGMs with the evanescent field of a phase-matched optical waveguide. The microcavity WGMs with its unique combination of strong temporal and spatial confinement of light have attracted increasing interest due to their high potential for a large number of applications in either fundamental research from quantum electrodynamics (QED) to nonlinear optics, as the realization of microlasers [1], high resolution spectroscopy [2], or in applied photonics and optical communications areas such as miniature biosensors [3], narrow filters [4], optical switching [5], etc. For the dielectric medium as a microsphere, mode volume can be as low as a few hundred cubic wavelengths with very high finesse. The Rare earth-doped (Er or Nd) glass are ideal subject for realizing these microspherical lasers with very high quality factors **Q**.

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B.R. Johnson theoretically studied the behavior of the morphology-dependent resonances of a dielectric sphere on or near a plane of infinite conductivity. His result shows that the locations and widths of the resonances change as the sphere approaches the surface [6]. If the sphere is initially located at a distance d that is more than approximately $2D/3$ away from the point of contact with the conducting plane, the resonances will have the same locations and widths as they do in an isolated sphere. Then, as the sphere is brought closer to the surface or eventually in contact with it, the locations and widths of the resonances change. The locations of the TE-mode resonances shift to higher size parameters ($i.e.$ Blue-shift in wavelength), the TM-mode resonances shift to lower size parameters ($i.e.$ Red-shift in wavelength) and the widths of both types of resonance increase. Most of the change in location and width occurs when the sphere is quite close to the conducting plane. Approximately 90% of the total resonance shift occurs when the distance from the point of contact is less than 0.05 of the diameter of the sphere. This presents the possibility of tuning the WGM wavelengths.

In this paper, we describe research results on laser realization using a tapered fiber for efficient coupling as well as wavelength shifting effect of the laser. Our experiments have been carried out for the $I_{13/2} \rightarrow I_{15/2}$ laser transition at 1550 nm of Erbium ions in phosphate glass microspheres.

2. Experiment

The material used for fabrication of microspheres was an Er^{3+}/Yb^{3+} phosphate glass (Schott IOG-2) doped with 2% weight of Er_20_3 and co-doped with 3% weight Yb_20_3. Microspheres have been produced from phosphate glass powder using a microwave plasma torch (oscillator frequency of 2.4GHz and maximum power of 2kW) with Argon is used as plasma gas and oxygen or nitrogen as sheath gas. Powders are axially injected and melt when passing through the plasma flame, superficial tension forces giving them their spherical form. The microwave power and gas discharges can be adjusted to obtain optimal conditions to spheroidize fluoride or silicate glass. The diameter of the spheres was varied from 10 to 200 μm depending essentially on the powder size. Free spheres are collected a few ten centimeters lower. Obtained spheres then are glued at the tip of optical fiber of about 10 μm to 30 μm in diameter which allow to manipulate them easily and to insert them in the setup.

The use of an Er^{3+}/Yb^{3+} co-doped phosphate glass is associated with the $975nm$ pumping wavelength in order to populate the $^2F_{5/2}$ metastable level of Ytterbium ions which transfer their energy to the neighboring Erbium ions by radiative and non-radiative ways. To take full advantage of this excitation mechanism, we chose $975nm$ among the different appropriate wavelengths for pumping Erbium/Ytterbium co-doped glasses ($810nm$, $975nm$ and $1480nm$) in our experiment. The pump source was fiber pigtailed SDLO-2564 $-$ 120 Laser Diode generating $976.1nm$ radiation with the maximum CW power of $120mW$. Also, we use a high doping concentration glass (1.710^{20} ions/cm^3 for Erbium and 2.510^{20} ions/cm3 for Ytterbium). The use of Ytterbium ions helps to avoid the side effects of a too high Erbium concentration (self pulsing etc).

2.1. Excitation and receiving of WGMs

Coupling light into and out of the microspheres must be realized by means of optical tunnel effect through evanescent field. For efficient coupling light into microspheres or to get WGMs signal out from micro sphere one must adjust the frequency of the excitation beam to a WGM resonance and align the excitation beam so that it also has an angular momentum matched the angular momentum of that mode. There are many different techniques for this purpose using high-index prisms, tapered fibers, angle polished fiber couplers or waveguides. Spheres must be set very close to the prism inside the evanescent field. In this experiment we use half-tapers for coupling light in and out because of its relatively simple in making and mounting technique. The coupling can be achieved if we put the microspheres very close to the half fiber taper tip. The distance between microspheres and fiber taper tip as well as an angle regarding microspheres's equator was controlled by micro positioning stages and/or with piezoelectric actuators. We produced the half tapers by chemical etching in HF or by heating and stretching a standard telecommunication single mode at 1.55 μm fiber until breaking it, using either CO_2 laser or fusion optical splicing system. The fiber tip was tapered to $\sim 2\mu m$ in diameter.

2.2. The experimental setup

The experiment (see Figure 1) was realized with standard fiber-optic components spliced or connected by APC connectors. Our experiments were performed with two direct fiber coupling scheme using half-tapered fiber: a) two separate half-tapers, one for coupling $980nm$ pump in (1.a), the other for coupling signal out from the sphere (Figure 1.a), and b) using one single half-taper to couple both pump emission in and the micro spherical laser out (Figure 1.b). The output $1.55\mu m$ laser radiation is coupled into the optical fiber and fed to Spectrum Analyzer.

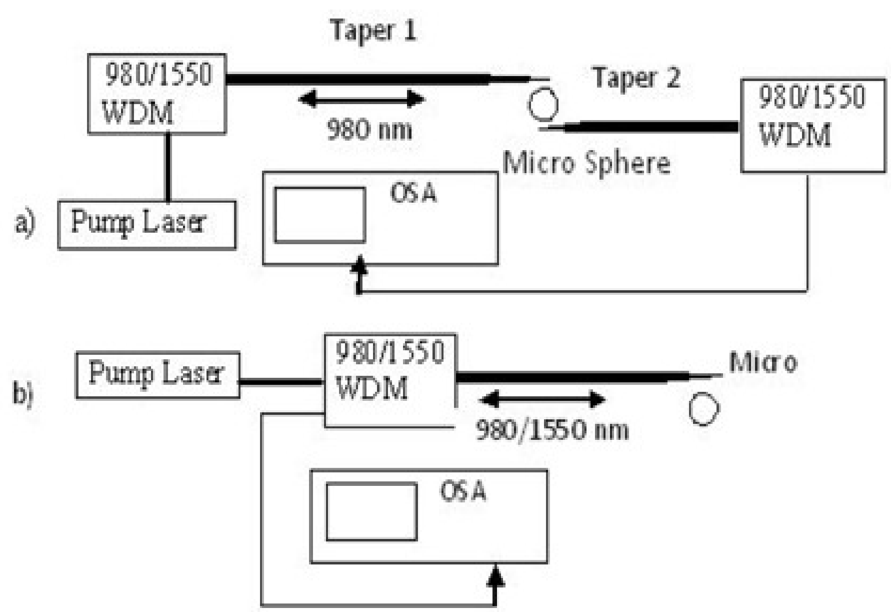
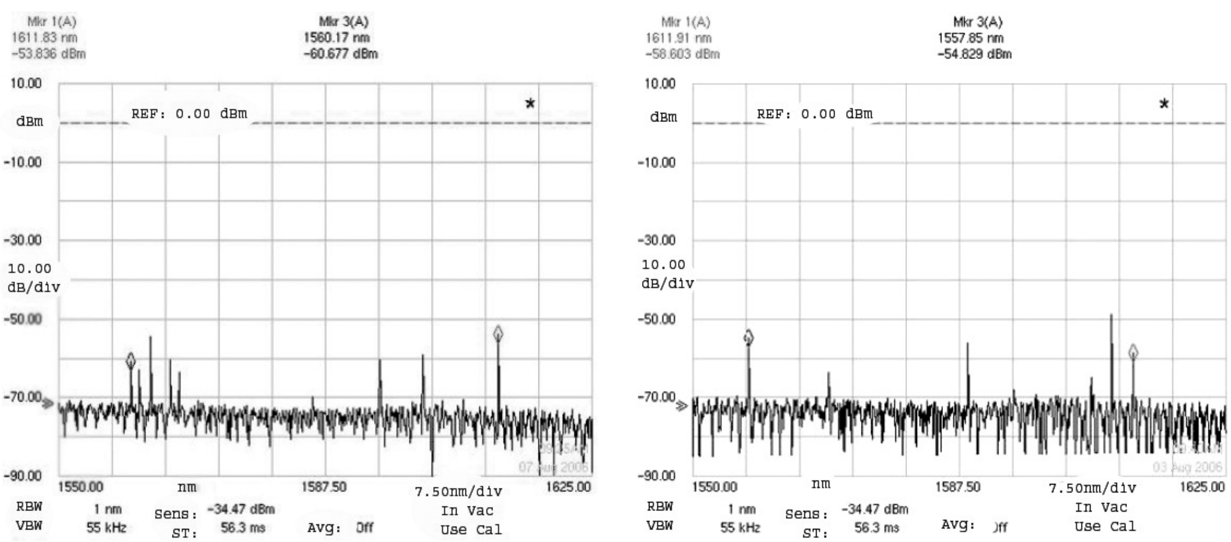


Fig. 1. The principal experimental setup: a) double half tapers; b) single half taper.

Although the optimum coupling conditions for two wavelengths, $\lambda \sim 975\mu m$ for the pump and $\lambda \sim 1.55\mu m$ for the laser signal are not the same, we received good results even in single half-taper scheme (See Figure 2). We fixed the co-doped Er^{3+}/Yb^{3+} phosphate glass microspheres but mounted half tapers on XYZ Linear Micro translations with Rotation Stage. This setup allows for establishing the equator region of the microspheres in the evanescent field surrounding the half taper and adjusting the acceptance angle (between the tip axis of the half taper and equatorial plane). The collected laser signal was analyzed with a 0.06nm resolution Optical Spectrum Analyzer (OSA - Model: Agilent 86142B).

3. Results and discussion

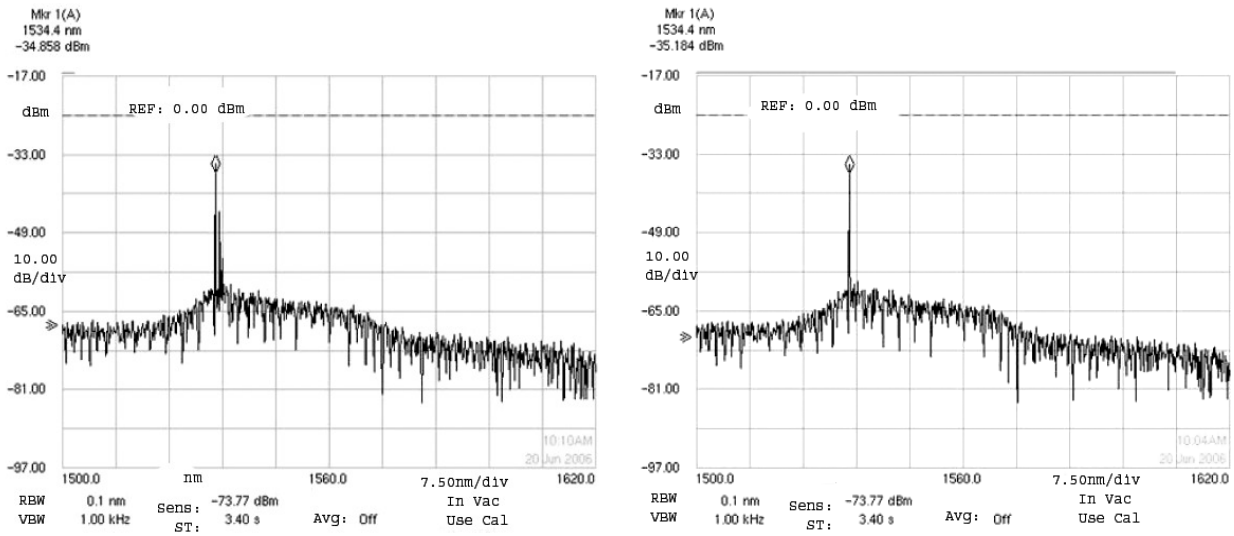
The excited micro sphere emitted strong green upconversion fluorescence along equatorial. Observed spectrum (by S2000 Spectrometer - Ocean Optics, USA) shows the existence of the red emission around $660nm$ besides the strong green emission around $545nm$. In the $1550nm$ region of the $I_{13/2} \rightarrow I_{15/2}$ transition of Er^{3+} ion the optical spectrum of the output signal from the sphere below the laser threshold presents the luminescence intensity with series of small peaks. Estimating the microsphere diameter through peaks distance in these spectrums gave result well matched the one received by optical method. When increasing the pump intensity we obtained laser oscillation. Because of the difficulty in quantifying pump portion coupled in sphere, we controlled only the total output power of LD pump. The actual pump power at the tip was approximately 70% of that value. Figures 2 presents several laser spectra from the microsphere of $140\mu m$ diameter under different total pump power.



a) b)

Fig. 2. The laser spectrum from microsphere of 140 µm diameter, total pump: 45mW (100mA): a) double half tapers; b) single half taper.

Successful collecting the laser emission from the microsphere depends on coupling half taper parameters. The form of the half taper i.e. length of tapered part of fiber affects the coupling efficiency as well. Sharp angle half taper (length about or more than $800\mu m$) makes it easier to collect signal while blunt angle half taper allows easier to select laser mode. By adjusting the coupling parameters (the microsphere - taper gap, the angle between the taper and microsphere equator...) we can extract laser radiation in certain wavelength region. The shortest observed laser line was $1532.2nm$ and the longest was $1618.9nm$. The WDM line width is limited by OSA resolution ($0.06nm$). In most cases a good coupling is obtained simultaneously for several lines with different wavelengths λ so we have observed multiline laser signal. The laser emission can be extracted even when the half tapers are in contact with the sphere, though in this case we may get simultaneously series of laser lines in broader range (from $1557.8nm$ up to $1611.9nm$, see Fig 2). The single laser line can be selected by varying the angle between half tapers axis and equatorial plane of the sphere in double taper scheme. Figure 3 presents an example of selecting a single laser mode at 1534.4 nm from three lines by changing the acceptance angle. Due to half taper non-constant diameter and consequently variable gap between the fiber and the microsphere, by choosing the coupling point in the half taper i.e. adjusting the distance from tip to acceptance point we may also find the appropriate position to select one lasing mode.



a) b)

Fig. 3. Selecting a single laser mode by changing the acceptance angle: a) three lines emission, marker at 1534.4 nm b) single line at 1534.4 nm.

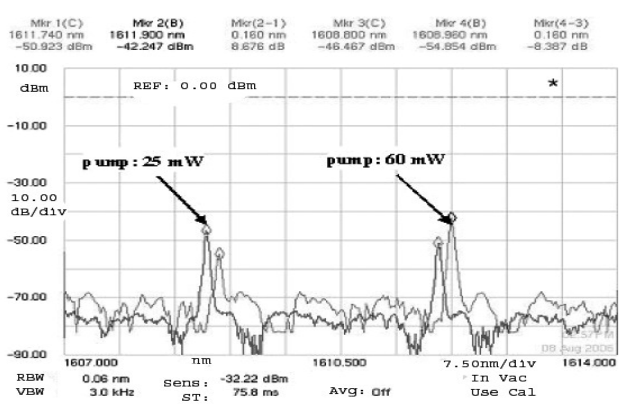


Fig. 4. The wavelength shift in laser spectrum, microsphere of 140 μm diameter, pump: 25 mW and 60 mW - shift right.

When increased the pump power we may collect some newly emerged laser lines beside those existed. We also observed red shift in the wavelength of WGMs. The typical result of the laser spectra analyzed by an Optical Spectrum Analyzer with a resolution of $0.06nm$ is illustrated in figure 4. The two wavelengths at $1608.80nm$ and $1611.74nm$ when the total pump power intensity was $25mW$, shifted further to $1608.96nm$ and $1611.90nm$, respectively, when total pump power was increased to $60mW$. Similar red-shift behaviors have also been observed for sphere other size. Except several new lines emerged under strong pump, all exist WGMs shifted by $0.16nm$ towards longer wavelength under the total power domain increasing from 25 to 60. This red shift phenomenon was experimentally observed in Er/Yb phosphate microchip laser [7] and explained by a model based on thermal effects [8]. The phonons inside active micro spherical laser cavity associated with the non radiative decay between the manifolds of Erbium ions, and between the intra-Stark levels of the laser manifolds, thus create thermal deposition and heat the microsphere. An increase of cavity temperature results in both an expansion of the microsphere cavity length and a change of index of refraction. Both changes then affect the lasing condition and shift the wavelength of every WGM.

We have investigated interaction between WGM lasers with the unprotected Aluminum flat mirror which is a good approximation of a conducting plane. The mirror was driven by micro translation stage with $10\mu m$ step from below the microsphere (Fig. 5). The microsphere has a diameter $D \sim 90\mu m$. The laser emission had been observed with the mirror at a distance $\sim 200\mu m$. When translating the mirror towards the sphere we observed a line shift towards the shorter wavelength (Fig. 6 - a). The change of the mode intensity is presented in Fig. 6 - b. The influence of the mirror is clear from $d \sim D$. For a lower wavelength, we have observed the same "blue" shift behavior (Fig. 7). The wavelength shift was $0.2nm$ for $1608.7nm$, $0.22nm$ for $1566.9nm$, $0.18nm$ for $1548.28nm$ and $0.16nm$ for $1535.75nm$ lines. We also observed that some lines do not shift but disappear.

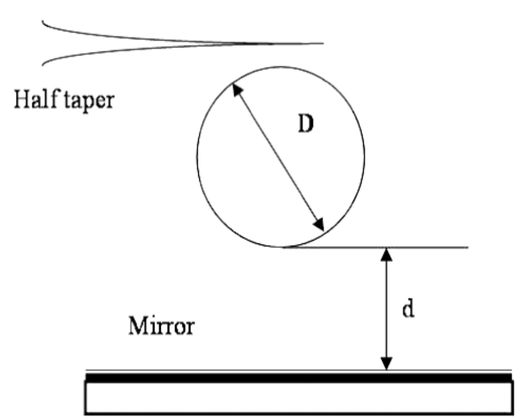
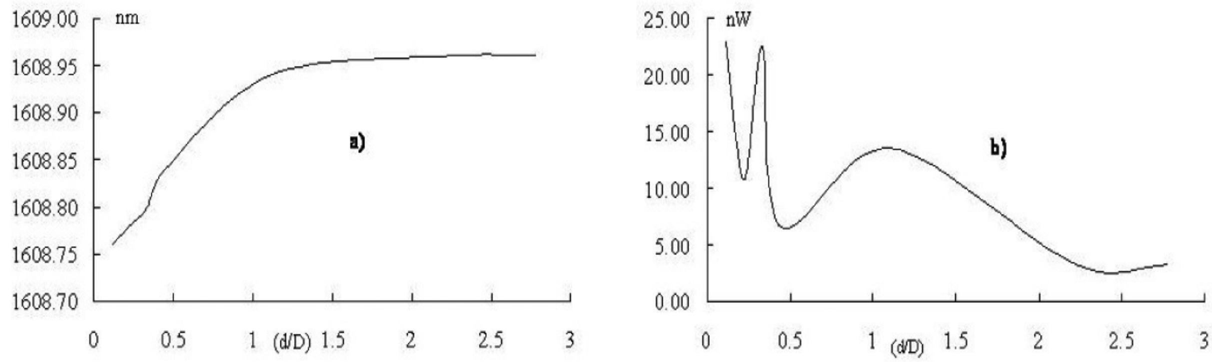
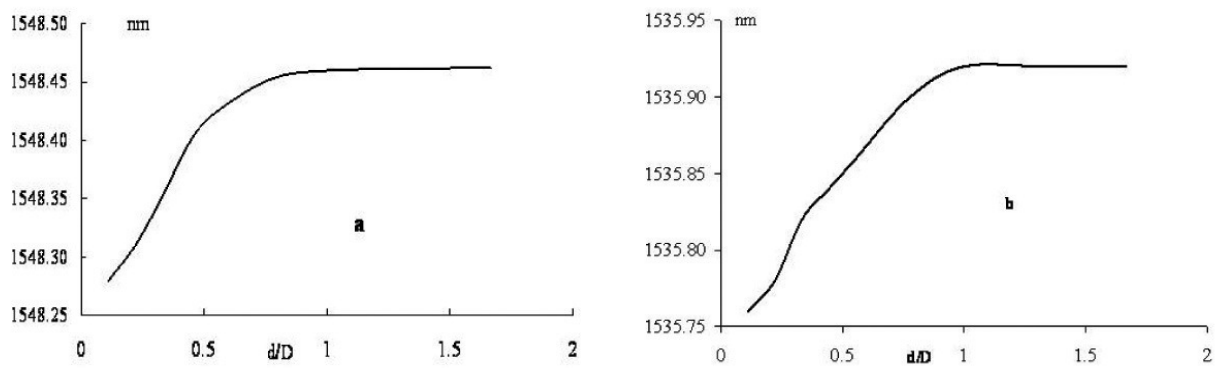


Fig. 5. Setup for the Sphere-Mirror interaction experiment.

Compare to Johnson's theoretical prediction of the WGM's behavior, our result shows that we observed the wavelength shift corresponding to TE modes. P. Feron et al. approached the shift of resonances predicted by Johnson from the effective potential point of view [9]. In their approach, for an isolated sphere, the radial equation is very similar to the Schrödinger equation with a pocket-like pseudo potential due to the refractive index discontinuity at the surface of the sphere. The mirror associated to a mirror reflection symmetry operation gives an even symmetric potential. Symmetric Φg and antisymmetric Φu eigenstates associated respectively to blue-shifted (symmetric) and red-shifted



a) b)
Fig. 6. Dependence from sphere-mirror distance of: a) Wavelength b) Intensity.



a) b)
Fig. 7. WGM wavelength shift of a) $1548.27nm$; b) $1535.76nm$.

(antisymmetric) wavelengths. Taking into account the vector aspect of TE and TM modes and that the electrical field is quasi-tangential to the sphere for TE modes (quasi-radial for TM modes) for a large diameter ($D > 20\lambda$), thus TE modes are associated only to symmetric states and TM to antisymmetric states. The model explained the resonance shift but it does not take into account the metallic properties of the mirror and could not give reasonable explanation on quenching of some modes observed. The coupling of the TM modes (electric field normal to the surface) with the surface waves of the metal plane may lead to their quenching.

The width of the laser mode is narrower than our experiment's equipment resolution, so we do not investigate its behavior.

4. Conclusions

The microsphere WGM lasers was realized in Er^{3+}/Yb^{3+} co-doped phosphate glass using $976nm$ pump, to take full advantage of energy transfer effect from ion Ytterbium to ion Erbium. The coupling was carried out by fiber half taper technique in two schemes, both gave good results. The single laser line power may reach $150nW$ with only $25mW$ total pump power, and laser range extends from $1532.2nm$ to $1618.9nm$. The red shift effect, which associated with the thermal effect occurred insider sphere took place under strong pump. We have experimentally observed only a emission wavelength shift by about $0.2nm$ to the shorter side (blue { shift) while varying the distance sphere-mirror from $100\mu m$ ($\sim$ D) to $10\mu m$ (~ 0.1D). The proposed red shift have not been confirmed.

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