Compensation of thermal nonlinear effect in hybrid microsphere resonators

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A hybrid structure with higher linearity to compensate the thermal refraction effect based on a ruby microsphere resonator is proposed and has been realised. The thermal refractive effect of the hybrid structure is theoretically and experimentally demonstrated, which showed that it is limited by the diameter of the resonator and the Q factor. By increasing the diameter, the transmission spectrum experiences a transition from blueshift to redshift induced by thermal absorption and when it is equal to a specific value the thermal refraction effect can be reduced or even eliminated. Experiments showed that there is no shift with varying input optical power since the thermal refraction of ruby can be completely compensated at the diameter of the microsphere $d = 1.5$ µm and $Q = 2.3 \times 10^6$ when the KD-310 coated thickness is 60 µm. This reported work shows that the structure could be used to improve stability and is sensitive in high-Q resonators for applications in laser, biosensor and nonlinear optics.

1. Introduction: Recently, there has been a growing interest in a type of resonators, that is the whispering gallery mode (WGM) resonators [1, 2], in which light is trapped in circular orbits by continuous total internal reflections from the circular boundary [3]. Optical glass microresonators, such as the microsphere [4], microrings [5] and microtoroids [6], which possess circular boundaries to support WGMs, have been intensively investigated for a variety of applications, including lasing [7], biosensing [8, 9] and nonlinear optics [10]. Nonlinear optical materials have been utilised because of their great flexibility of material composition and use in resonators. Therefore, they could be directly implemented in a wide range of applications such as wavelength conversion, optical switching and signal regeneration, which have the potential to radically transform future optical communication networks [11].

Stability of the resonant wavelengths is of great importance in such applications. In practical applications, the transmission spectrum is sensitive to the input power, which dramatically affects the stability. To overcome this problem, we propose and have realised a hybrid structure to compensate the thermal refractive effect by coating a KD-310 layer to the surface of the resonator.

2. Theory: The thermal nonlinear effect takes place in dielectrics with non-zero optical absorption and results from the change of the refractive index of the substance under heating produced by the partial absorption of light. It can be characterised by the thermal refractive and expansion coefficient of the material [12].

In this reported work, the ruby microsphere resonator is coated with a low refractive index ultraviolet glue KD-310, which has a large negative thermal refractive coefficient of -95×10^{-6} [13]. The shift of the resonant transmission, which is caused by thermal changes, can be expressed as [14]

$$\Delta\lambda = \lambda_0\left[\varepsilon_{eff} + \frac{1}{n_{\mathrm{eff}}}\cdot\frac{\mathrm{d}n_{\mathrm{eff}}}{\mathrm{d}T}\right]\Delta T \tag{1}$$

where $\Delta\lambda$, $\varepsilon_{\mathrm{eff}}$ represent the resonance wavelength and the effective expansion, $\mathrm{d}n_{\mathrm{eff}}/\mathrm{d}T$ and n_{eff} represent the thermal optic coefficient and the effective refractive index. For a hybrid structure, the thermal optic coefficient $\mathrm{d}n_{\mathrm{eff}}/\mathrm{d}T$ and the effective refractive index n_{eff} should be modified as [15]

$$n_{\mathrm{eff}} \simeq \eta_1 n_1 + \eta_2 n_1 \tag{2}$$

$$\frac{\mathrm{d}n_{\mathrm{eff}}}{\mathrm{d}T} = \eta_1\frac{\mathrm{d}n_1}{\mathrm{d}T} + \eta_2\frac{\mathrm{d}n_2}{\mathrm{d}T} \tag{3}$$

where $\mathrm{d}n_1/\mathrm{d}T$ and $\mathrm{d}n_2/\mathrm{d}T$ represent the thermal refractive coefficient of ruby (positive) and KD-310 (negative), respectively. η_1, η_2 indicate the fractions of light energy travelling in the ruby microsphere and the KD-310 layer, respectively. The sum of η_1, η_2 should be approximately equal to 1 when the light energy out of the KD-310 in air is negligible. To eliminate the thermal resonance shift in the hybrid structure, the ratio of η_1/η_2 needs to be adjusted so that $\Delta\lambda \simeq 0$.

For the hybrid structure, the ratio of the thermal refractive coefficient of ruby and the KD-310 is around 1:7.5; therefore, the fraction η_1 of ruby should be 85.9% (the diameter of ruby should be 1.58 mm) to completely compensate the positive thermal refraction effect.

Fig. 1 shows the theoretical resonant wavelength shift at 1550 nm against temperature based on (1). As can be seen, by increasing the

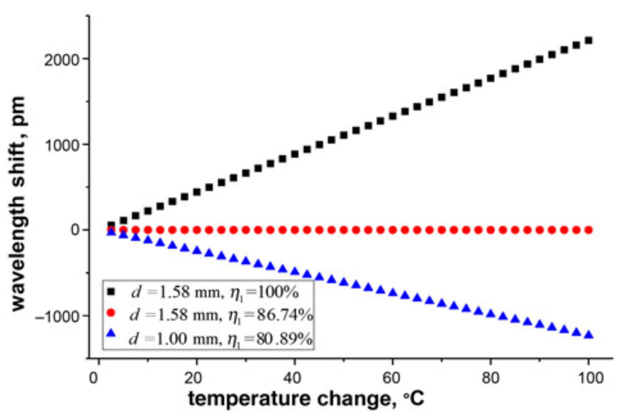

Figure 1 *Theoretical resonant wavelength shift at 1550 nm against temperature*

fraction η_1 of ruby, the transmission spectrum experiences a transition from blueshift to redshift. The thermal refraction effect can be compensated when η_1 is equal to 85.9%.

3. Testing and results: Fig. 2 shows a ruby resonator which is KD-310 coated with a dispensing gun at a constant thickness of 60 µm since it has low surface tension.

The experimental setup for the thermal nonlinear effect is shown in Fig. 3. The tapered fibre was fabricated using the 'brush flame' technique [16]. The resonator was mounted on a precise transportation platform which can finely control the distance between the tapered fibre and the resonator over a range of a few nanometres. To ensure the reliability of testing results, the coupling distance was controlled from undercoupled to critically coupled. WGMs were excited by a tunable laser with a centre wavelength of 1550 nm (New Focus TLB-6700, linewidth < 300 kHz) through a polarisation controller and hybrid resonator structure. A triangle wave signal with 50 Hz was used to connect to the laser forming a fine scan of the WGMs. The scanning range was 15 GHz, resulting in the transition time of the WGM being smaller than 667 µs, which is much shorter than the time of the thermoexpansion behaviour (tens of milliseconds). Therefore, the thermal refractive effect is predominant in the thermal dynamic process. To observe the transmission spectral and the resonant wavelength, the output signal was collected using an InGaAs photodetector (New Focus 1811-FC) and an oscilloscope.

To study the thermal refractive effect of the hybrid structure, two different hybrid resonators including ruby and silica resonators were investigated as shown in Fig. 4. It clearly reveals the resonant shift as an increasing input power which induces the thermal refractive effect.

To analyse the thermal refractive effect intuitively, the shift of resonant transmission is plotted in Fig. 5. As can be seen, the linearity of the ruby resonator is better than the silica resonator. One possible reason is that ruby is more stable in its physical and chemical properties which makes it less susceptible.

A detailed experiment based on the ruby microsphere was carried out to compensate the thermal refractive effect and the following testing parameters were constant: (i) coating thickness, (ii) scan rate and scan range and (iii) the taper length, taper waist diameter, and resonances which are not split were used. In addition, the

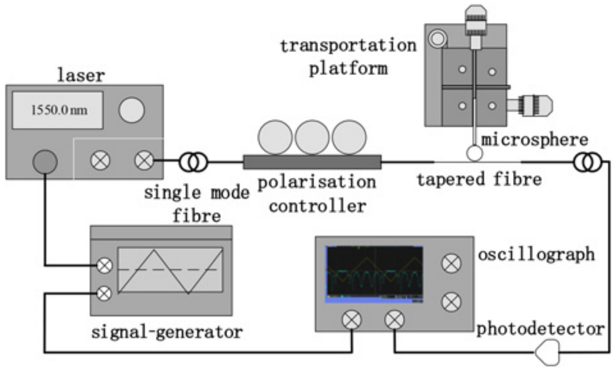

Figure 3 *Experimental setup for thermal nonlinear effect*

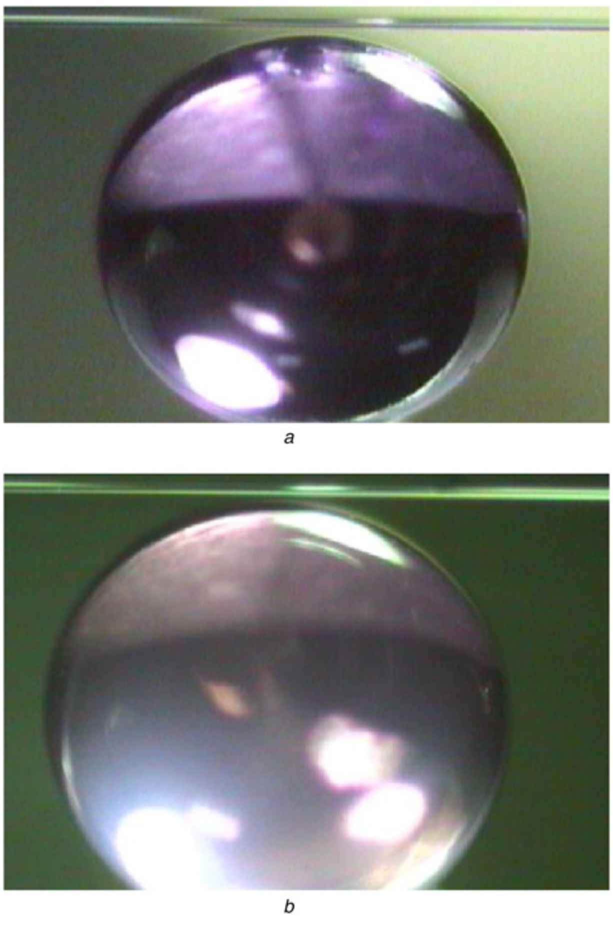

Figure 2 *Microscopic image of ruby microsphere with diameter of 1 mm and of hybrid structure with coated thickness of 60 µm*
a Ruby microsphere
b Hybrid structure

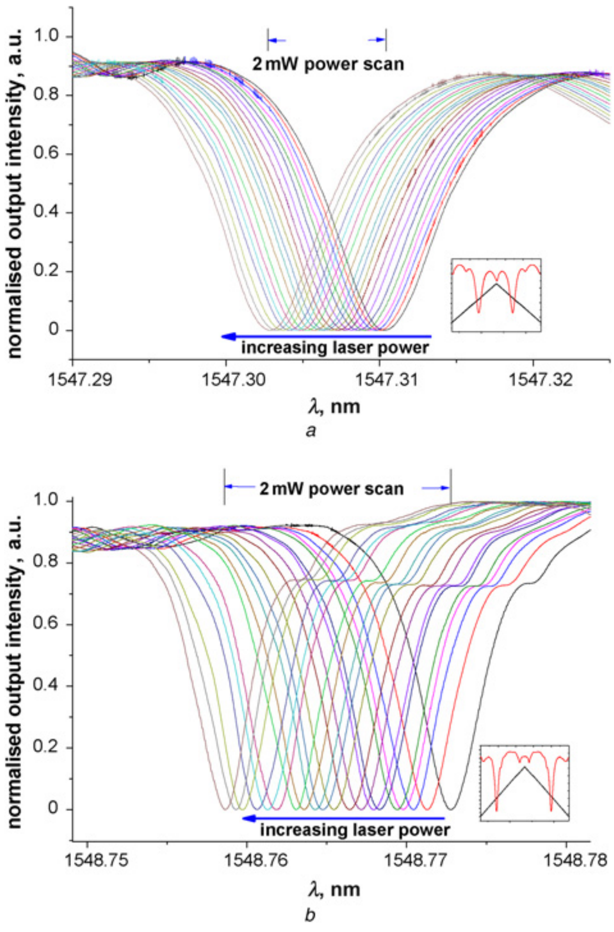

Figure 4 *Resonance shift of ruby microsphere and of silica microsphere*
a Ruby microsphere
b Silica microsphere

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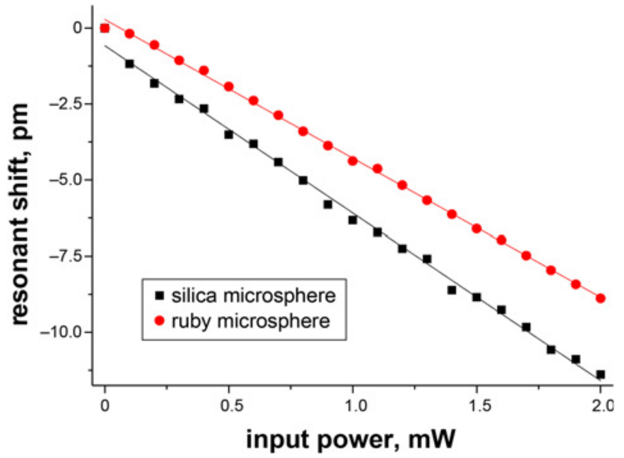

Figure 5 *Practical resonant wavelength shift of silica and ruby hybrid resonator against input power*

resonator was set in a thermostat to minimise the error resulting from peripheral temperature variation. To compensate the thermal refractive effect in the hybrid structure, different diameters of the ruby microsphere were compared, see Fig. 6.

As can be observed, the resonance shift in the hybrid structure depends on the diameter and Q factor of the hybrid structure. Only at the diameter $d = 1$ mm, the resonant transmission is blue-shifted, the fraction $\eta_1 \simeq 81.10\%$ is smaller than 85.9% leading to over-compensation. When $d = 1.58$ mm and $d = 2$ mm, the resonant transmission is redshifted and the fractions $\eta_1 \simeq 88.29$ and 90.82%, respectively, are larger than 85.9%, resulting in under-compensation. However, when the ruby diameter $d = 1.5$ mm, the fraction $\eta_1 \simeq 86.64\%$ and the Q factor is about 2.3×10^6, the positive thermal refraction effect is completely compensated by the KD-310 coated layer, which is in excellent agreement with the theoretical value of 85.9%. The slight difference between the theoretical and the practical result is because of the thermal expansion effect is not taken into account in the experiments.

For long-term applications, stability experiments were also carried out. Fig. 7 shows the shift against the elapsed time of the same hybrid structure resonator which is compensated by the thermal refractive effect. For a long time, the resonant wavelength of the hybrid structure has a relatively high stability. Moreover, when the input power is below 4 mW, the shift of the transmission spectrum is extremely small, which is probably due to several factors including temperature oscillations and ambient vibrations

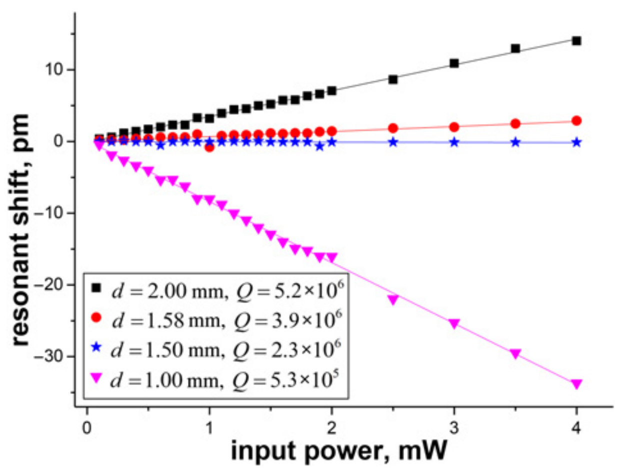

Figure 6 *Resonant wavelength shift of different ruby microsphere diameters against input power*

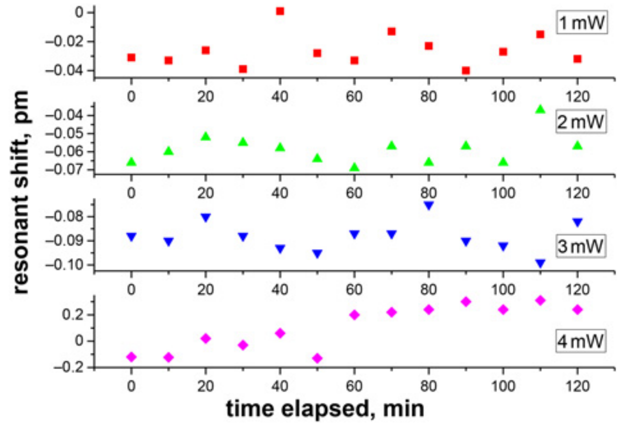

Figure 7 *Shift against elapsed time of the same hybrid structure resonator at different input powers*

during the measurement. While the input power is equal to 4 mW, the shift of transmission has obvious fluctuations. The main reason is that the input power is great enough to increase the hybrid structure temperature strikingly so that the absorption of heat could change both the refractive index and the geometry of the hybrid structure.

4. Conclusion: By contrasting the ruby hybrid structure with the silica hybrid structure, it is demonstrated by experiments that the ruby hybrid structure obtains better linearity. The thermal refractive effect of the hybrid structure was analysed theoretically and experimentally, which demonstrate that it is limited by the diameter of the resonator and the Q factor. As in the experiments, the positive thermal refractive effect can be completely compensated with the diameter of the microsphere $d = 1.5$ µm and the $Q = 2.3 \times 10^6$ when the coated thickness is 60 µm. The ruby hybrid structure has theoretical predictability and stability, which provides a reliable resonant wavelength over a wide range of input power. This could play an important role in laser, biosensor and nonlinear optics.

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