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Thermo-Optical Tuning of Whispering-Gallery Modes in Er:Yb Co-doped Phosphate Glass Microspheres

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We demonstrate an all-optical, thermally-assisted technique for broad range tuning of whispering gallery modes in microsphere resonators fabricated from an Er:Yb co-doped phosphate glass (IOG-2). The microspheres are pumped at 978 nm and the heat generated by absorption of the pump expands the cavity, thereby altering the cavity size and refractive index. We demonstrate a significant nonlinear tuning range >700 GHz of both C- and L-band cavity emissions via pumping through a tapered optical fibre. Finally, we show that large linear tuning up to ~488 GHz is achievable if the microsphere is alternatively heated by coupling laser light into its support stem.

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1. INTRODUCTION

Spherical whispering gallery mode (WGM) resonators can be used in a broad range of applications from bio-sensing [1] to laser engineering [2]. Beyond the interest for applied studies, such resonators are also of interest for more fundamental studies, e.g. cavity QED [3, 4]. A key requirement for many applications is the ability to tune the resonator to an energy transition of the atomic species (or material) under investigation. Various methods for tuning microcavities have already been explored, e.g. external heaters [3-5], pressure/strain techniques [6, 7], and electro-optical [8], electro-thermal [9] and thermo-optical [10] effects. All of these methods result in relatively small tuning ranges of < 300 GHz. More recently, larger tuning ranges have been demonstrated using opto-mechanical tuning [11], strain tuning of a bottle resonator [12] and electrical tuning of liquid crystal micro-resonators [13].

In this paper thermo-optical methods for tuning the WGM resonance frequencies of doped glass microspheres over a large dynamic range are demonstrated. Er:Yb phosphate glass (Schott IOG-2) microspheres are pumped at 978 nm via a tapered optical fibre. This causes internal heating of the microsphere, with the heat concentrated in the optical mode volume, leading to nonlinear tuning of ~700 GHz. Alternatively, the sphere can be heated more uniformly by optically pumping through its supporting stem. This avoids pump/cavity resonances and results in linear tuning of the cavity modes.

2. EXPERIMENTAL DETAILS

The IOG-2 glass used is doped with 3 wt% Er_2O_3 (2.5×10^{20} ions/cm^3) and co-doped with 5 wt% Yb_2O_3 (4.2×10^{20} ions/cm^3). Lasing and upconversion fluorescent emissions are studied following continuous pumping with 978 nm laser diodes. A schematic of the experimental setup is shown in Fig. 1. Pump1 is used to generate 1550 nm lasing modes within the resonator and efficient coupling is attained via adiabatically tapered optical fibres [14] fabricated using a direct heat-and-pull technique, using an oxy-butane torch as the heat source. The tapered fibres have diameters of ~ 1 μm and the fibre losses are typically less than 20%. When the sphere is in direct contact with the tapered fibre a dip of about 20% in transmitted pump power is observed and it is assumed to be off-resonance. The power of pump1 is adjusted using an electronically controlled variable attenuator. The upconversion spectrum scattered from the microsphere is collected in free space using a large core, multimode fibre connected to a CCD spectrometer (Ocean Optics USB4000). When required, a second 978 nm FBG diode laser (pump2) is used to send light up through the fibre stem, with a 20 μm tip, that is attached to the microsphere using UV curing glue and is used for sphere manipulation.

3. RESULTS AND DISCUSSION

The main transition processes for Er:Yb phosphate glass pumped around 978 nm have been extensively described elsewhere [10, 15, 16]. Boltzmann statistics can be used to describe the strong thermal coupling and the population redistribution between the $^2H_{11/2}$ and $^4S_{3/2}$ erbium energy levels that lead to green emissions at 530 nm and 554 nm respectively on decay to the $^4I_{15/2}$ state. The emission intensity ratio (530 nm/554 nm) from these two levels is a function of the cavity mode temperature [10, 15, 16]. The calculated temperature can be calibrated using the material's known thermal expansion coefficient [17] and, thence, the thermal shift rate of the cavity modes can be obtained. Applying the spectroscopic data in [16] to the IOG-2 sphere in this work, the temperature as a function of the 530:554 intensity ratio can be plotted and this is shown in Fig. 2

The largest measured 530:554 nm intensity ratio for IOG-2 is 3.5, equivalent to a temperature over 800 K [18]. This temperature is high compared to the glass transition temperature of 648 K [17]. However, it is important to emphasize that the calculated temperature does not represent the temperature of the bulk material, but only that of the mode volume. Heat dissipation from this region through the remainder of the material would account for no evident thermal stress on the sphere at temperatures lower than 800 K. Increasing the 530:554 nm intensity ratio to greater than 3.5 would, however, cause thermal damage of the microsphere [18].

Any increase in the microsphere temperature, δT, leads to a longitudinal expansion, δd, of the microcavity and a change in the refractive index, δn, of the material. The effect of these changes on the cavity resonance position, $\delta\lambda$, can be estimated from [10, 16]

$$\delta\lambda = \lambda\left(\frac{1}{n}\frac{\delta n}{\delta T} + \frac{1}{d}\frac{\delta d}{\delta T}\right)\delta T\,, \tag{1}$$

where λ is the resonance wavelength, $d = 2\pi R$, and R is the microsphere radius.

The IR emission cross-section of IOG-2 spans over 150 nm and a 20 nm window within this range is recorded on an optical spectrum analyzer. The IR spectrum detected from a 35 μm IOG-2 sphere is shown in Fig. 3(a) and the Q factor of the modes is greater than 10^5 (measurement limited). Eight WGMs are identified and the peak positions are recorded as the launched pump power through the fibre taper is increased from 10 μW to 45 mW as shown in Fig. 3(b). Note that pump2 is switched off during these measurements. The launched pump power is increased in steps of 900 μW for the first ten steps and then in 4.5 mW steps. The total frequency red shift for each mode is 460 GHz (or 3.68 nm). Using the glass manufacturer's quoted thermal expansion of $\delta d/\delta T = 145\times 10^{-7}$ K^{-1} [17] this equates to a temperature rise of 165 K, yielding a total shift rate of 0.022 nm/K. The temperature corresponding to each point is also estimated from the green upconversion fluorescence ratios. The initial temperature of the microsphere is ~345 K, while the maximum temperature recorded is ~515 K. This yields a thermal expansion rate of $\delta d/\delta T = 140\times 10^{-7}$ K^{-1}, which is ~3% less than that quoted by the manufacturer for this temperature range. The change in refractive index is assumed to be negligible [10, 15], since it is typically ten times smaller than the cavity expansion rate.

The tuning range in Fig. 3(b) can be divided into three distinct regions: (A) between 0.9 mW and 5.4 mW the slope is 0.22 nm/mW and is followed by a sharp jump in wavelength (1.58 nm) for all modes. This jump is caused by a sudden build up of pump power in the cavity due to a coincidental pump/cavity resonance condition, thereby creating a sharp increase in temperature (and fluorescence intensity) and a fast cavity expansion. In (B) the slope reduces to 0.15 nm/mW and in (C) the slope is further reduced to 0.014 nm/mW. Increasing the launched pump power into the tapered fibre above ~70 mW results in the sphere melting and fusing to the fibre [18]. Pump/cavity resonances caused by sharp spectral features in the pump field, and the resulting bistable behaviour [19-21], means that the tuning is generally nonlinear [see Figs. 3(b) and 4(a)]. Thermal feedback near such a resonance condition makes it difficult to control the tuning in this region. Occasionally, up to 75% of the tuning range can result from these resonant jumps. In contrast, the resonant jumps are not always observed and, in this case, the maximum tuning range is linear and typically ~300 GHz. Fig. 4(a) shows the measured tuning ranges for three different IOG-2 microspheres tuned by increasing the pump power into the fibre taper. All plots in Fig. 4(a) show strong nonlinear behaviour, but demonstrate the possibility of a large tuning range up to 700 GHz.

Finally, tuning of the WGMs of a microsphere by pumping up through the support stem with 978 nm pump light (pump2 in Fig.1) is demonstrated. Pump1, connected to the fibre taper, is reduced to a minimum and is only used to generate the 1550 nm WGMs within the cavity. The pump light entering the cavity via the stem does not generate coherent WGMs, but rather dissipates within the sphere, heating it more uniformly. Using this method linear tuning up to 488 GHz has been observed, as shown in Fig. 4(b). Note that it is still possible for the microsphere to become resonant with the pump light (pump1) in the fibre taper. However, by keeping this pump power to a minimum, significant resonant jumps are avoided and linear tuning via the stem is demonstrated. The pump/cavity resonances and the shifting WGMs lead to optical bistability in glass microspheres. The chance for occurrence of a pump/cavity resonance (between the light in the fibre taper and the cavity) may be reduced by using a broad amplified spontaneous emission (ASE) pump source with no sharp spectral features. However, a high pump power would be needed to achieve a tuning range larger than 300 GHz. Alternatively, using an ASE source (or a low power single mode pump) to generate the lasing WGMs and a cheap, high-power 978 nm laser pumped through the stem, larger linear tuning ranges should be achievable.

4. CONCLUSION

In conclusion, linear and nonlinear wavelength evolution of WGMs in Er:Yb co-doped glass microspheres as a function of launched pump power has been demonstrated. The IR fluorescence and/or lasing WGMs in some of the microspheres show large, nonlinear shifts of >700 GHz. The nonlinear behaviour is attributed to coincidental pump/cavity resonance conditions. Linear shifts up to ~488 GHz were demonstrated by uniformly pumping the microsphere via its support stem as opposed to using the taper coupler.

Small thermo-optically induced resonance shifts of ~100 GHz have previously been observed in erbium-doped fluoride glass (ZBLALiP) microspheres pumped at 1480 nm [10]. The fluoride glass spheres have a thermal expansion coefficient of $\delta d/\delta T \approx 87\times10^{-7}$ K^{-1}. However, the melting point of fluoride glasses is typically lower than that of phosphate glass and thermal damage, therefore, becomes an issue. In addition, the phonon energy in fluoride glass is typically less than 500 cm^{-1} making the heating process less efficient than in a phosphate glass. Themo-optically induced shifts in undoped silica glass, when pumped at 1545 nm, are of the order of 1.5 – 2.5 GHz/K and only a few degrees of heating is possible in undoped silica glass due to pump absorption [20]. The thermal expansion coefficient of silica glass $(\delta d/\delta T \approx 5.5\times10^{-7})$ is typically much less than that of phosphate glass. However, due to the higher melting point, it may be possible to use Yb:Er doped silica microspheres to achieve larger tuning ranges.

The approach used here to tune the cavity has advantages over other methods due to its reduced footprint, since it removes the need for bulky electrical contacts or mechanical components, thereby bringing the system closer to an integrated package. The doped microsphere could be thermo-optically tuned to arbitrary probe wavelengths for sensing applications and this will be the focus of future work.

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FIGURE CAPTIONS

Fig. 1. (Colour online) Schematic of the experimental setup. OSA: optical spectrum analyzer, WDM: wavelength division multiplexer, 90/10: 90:10 coupler. Inset: image of the microsphere on its fibre stem and the coupling taper.

Fig. 2. Calculated and measured temperatures for increasing 530 nm/554 nm intensity ratios in an IOG-2 microsphere.

Fig. 3. (Colour online) (a) Eight WGM resonances from a 35 μm IOG-2 microsphere. The pump power was initially below the microsphere's IR lasing threshold. As the pump power increases the peak intensities grow from a few pW to a few μW for the lasing modes. (b) Evolution of the eight WGM peak wavelength positions as pump power is increased.

Fig. 4. (Colour online) (a) Tuning of WGMs by increasing the pump power (pump1) in the tapered optical fibre. (b) Tuning of WGMs by increasing the pump power (pump2) in the stem. The series marked by the red stars are from the same microsphere. The tuning ranges in (b) were only limited by the power of our pump2 laser (maximum ~250 mW).

FIGURE 1

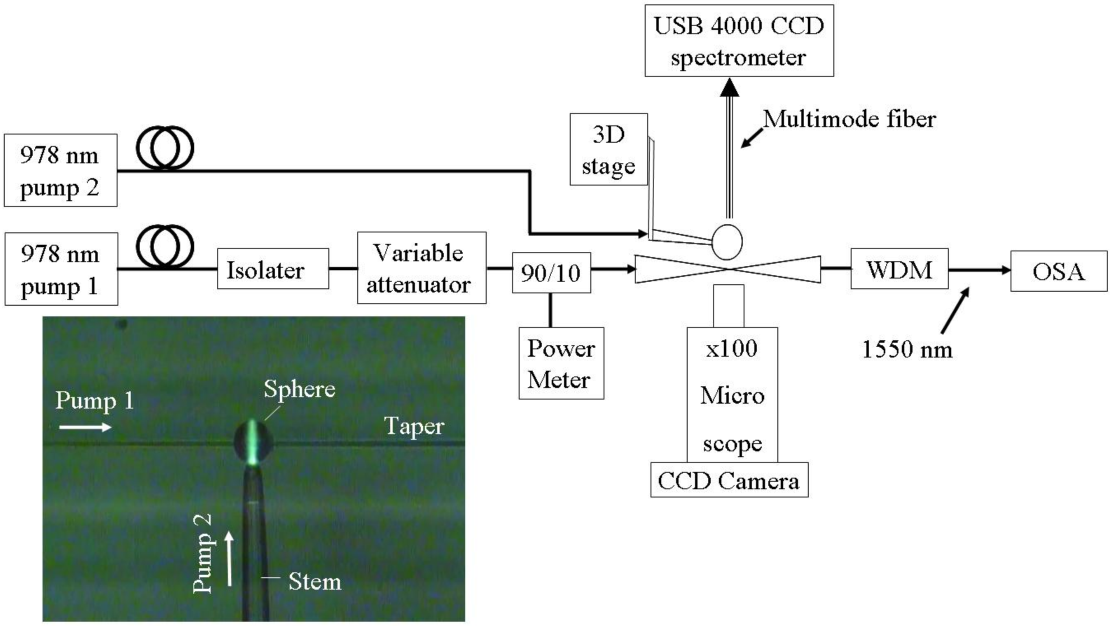
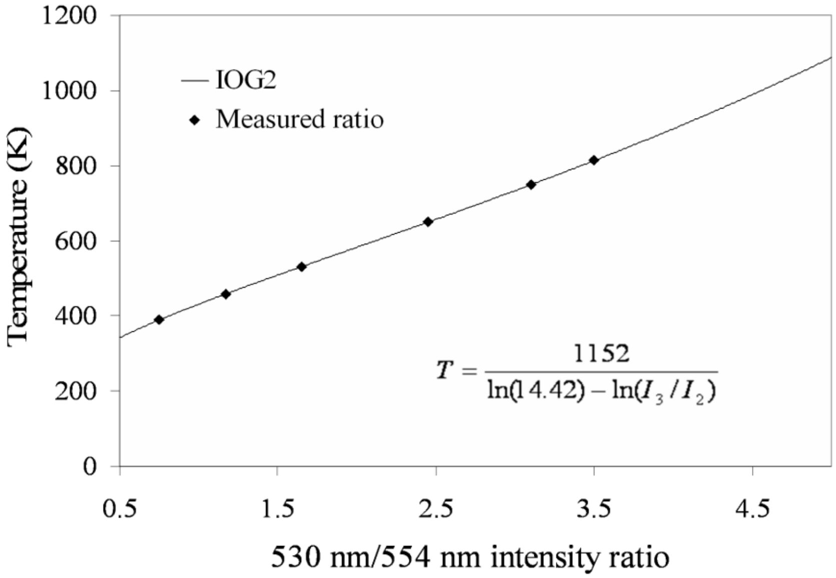
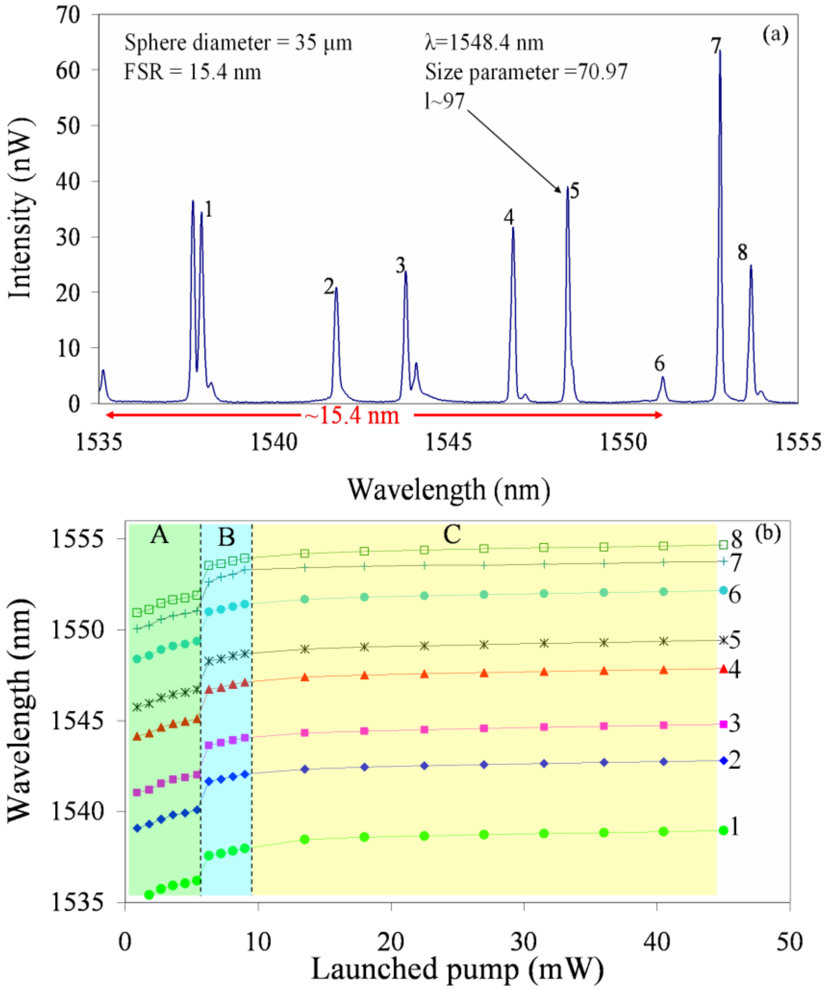

USB 4000 CCD spectrometer
Multimode fiber
3D stage
978 nm pump 2
978 nm pump 1
Isolater
Variable attenuator
90/10
Power Meter
WDM
OSA
1550 nm
x100 Micro scope
CCD Camera
Pump 1
Sphere
Taper
Pump 2
Stem

FIGURE 2



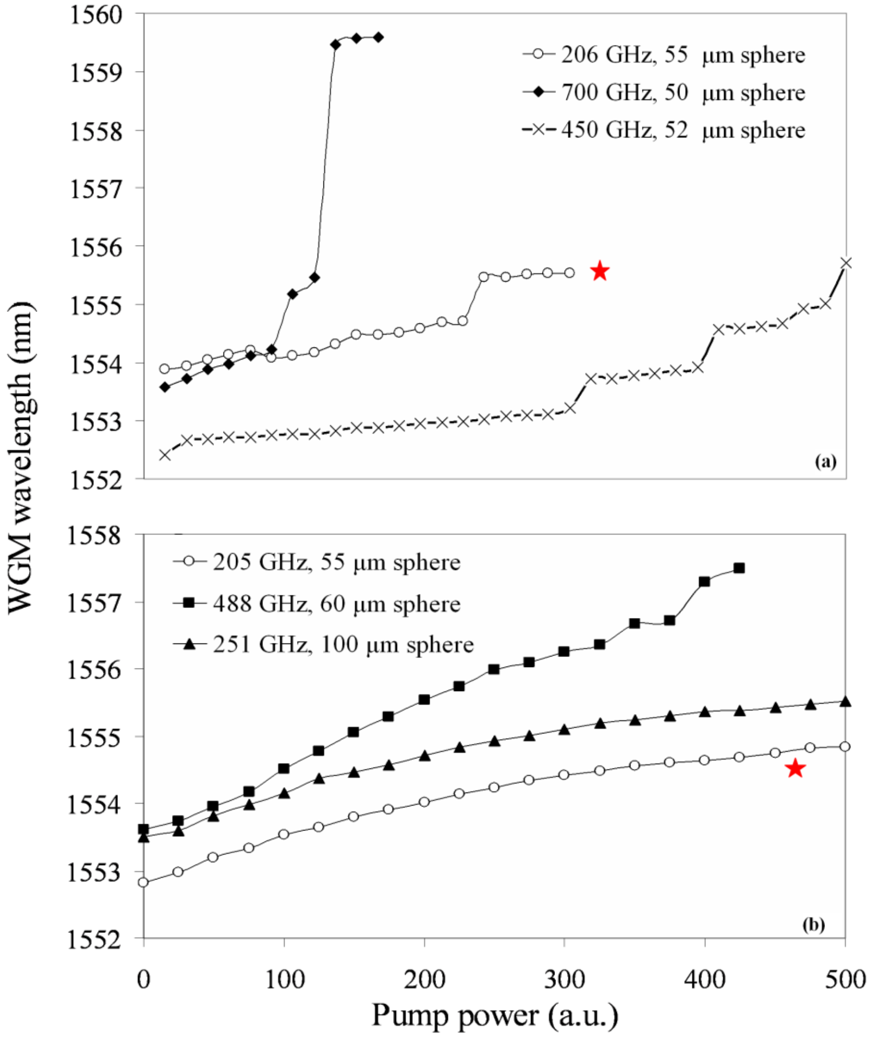
1200
1000
800
600
400
200
0
Temperature (K)
— IOG2
◆ Measured ratio
$T = \frac{1152}{\ln(14.42) - \ln(I_3/I_2)}$
0.5
1.5
2.5
3.5
4.5
530 nm/554 nm intensity ratio

FIGURE 3



Sphere diameter = 35 μm
FSR = 15.4 nm
λ=1548.4 nm
Size parameter =70.97
l~97
(a)
1
2
3
4
5
6
7
8
~15.4 nm
Intensity (nW)
70
60
50
40
30
20
10
0
1535
1540
1545
1550
1555
Wavelength (nm)
A
B
C
(b)
8
7
6
5
4
3
2
1
Wavelength (nm)
1555
1550
1545
1540
1535
0
10
20
30
40
50
Launched pump (mW)

FIGURE 4



1560
1559
1558
1557
1556
1555
1554
1553
1552
206 GHz, 55 µm sphere
700 GHz, 50 µm sphere
450 GHz, 52 µm sphere
(a)
WGM wavelength (nm)
1558
1557
1556
1555
1554
1553
1552
205 GHz, 55 µm sphere
488 GHz, 60 µm sphere
251 GHz, 100 µm sphere
(b)
0
100
200
300
400
500
Pump power (a.u.)