Microsphere laser developments for potential gas sensing applications

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Abstract. This paper presents preliminary results obtained from research into the development of a microsphere fibre laser designed for use in a compact gas sensor system. In this paper the focus is on achieving the optimum coupling between the microsphere and the tapered fibre used and obtaining the potential ultra-low threshold of the laser system.

1. Introduction

Laser sources operating in the mid-infrared are particular useful for gas detection as most of the ‘fingerprint’ absorptions of a range of gases lie within mid-infrared part of the spectrum. Infrared absorption techniques provide both a specific and direct measurement of gas species of interest and the approach does not rely upon using a secondary medium such as a chemically transductive material, which may make the measurement subject to error. Better environmental monitoring is the driver for creating more compact and efficient sources operating in this spectral region where LED sources are often unavailable commercially.

To create such effective laser sources at these wavelengths, fibre lasers have been exploited using their nature as compact, wavelength selectable devices. Dopants such as erbium, ytterbium and thulium in the fibre medium offer gain over limited spectral regions and the nonlinear effect of stimulated Raman scattering (SRS) provides for gain at many wavelengths, including the infrared, with the provision of suitable pump sources [1]-[6]. The threshold of these lasers, however, is often high and thus there is a requirement for a high power pump source. This limitation can be overcome by using a microsphere laser cavity as it has high a Q-factor which enables a large reduction in the necessary threshold pump power (a threshold as low as 86 µW was reported for a 40 µm silica sphere pumped at 1550 nm), while fibre coupling notably improves the overall efficiency and provides a convenient method of optical field transport [7]-[13]. Both Er³⁺ [14]-[16] and Tm³⁺ doped [17]-[19] micro-laser-cavities based on a variety of host materials have been reported and laser operation has been successfully achieved when they are coupled to various fibre tapers.
In this work, the experimental implementation of a microsphere Er doped fibre laser has been undertaken and discussed, with the relevant theoretical background.

2. Theoretical estimation of microsphere laser components

Inside the microspheres used, the whispering gallery modes (WGMs) with the lowest radial modes are of interest as they are confined near the surface with a small modal volume so that the light is trapped within the microstructure by total internal reflections near the surface and light orbits in a circle around the sphere. The WGMs can be evanescently coupled in or out using prisms, angle polished fibres or tapered fibres [20]-[22] and of these, tapered fibres are preferred because of the high coupling efficiency demonstrated and their ease of handling. In this paper, a simple model based on the method proposed by Knight et al [9] has been employed to calculate the coupling efficiency between the microspheres and the tapered fibres of different dimensions in the system design.

2.1 phase matching

To achieve the maximum coupling efficiency between a microsphere and a tapered fibre, phase matching is required where the propagation constant of the fibre taper should be matched to that of the microsphere [9].

For a tapered fibre, the high-order modes will be lost at the non-launch end and only the fundamental mode will exit, hence the propagation constant can be easily calculated as [9]

\[ \beta^2 = k^2 N^2 - \frac{2.405^2}{\rho^2} \]

(1)

where \( k \) is the free-space propagation constant of the light, \( N \) is the refractive index of the fibre, and \( \rho \) is the radius of the tapered fibre.

The whispering gallery modes inside a microsphere are characterized by several key parameters, termed \( q, l, m \), which represent respectively the of the radial, angular and azimuthal mode numbers. The propagation constant of the microsphere can be calculated on the basis of expressions for the WGM size and for angular characterization of the modes [23] and it is given by equation (2)

\[ x_q = \frac{\nu}{n_c} - \frac{\xi_q}{n_c} \left( \frac{\nu}{2} \right)^{\frac{1}{3}} + \sum_{k=0}^{k_{\text{max}}} d_k \left( \frac{n_c \xi_q}{\nu} \right) \frac{n_c - n_l}{n_c + n_l} \]

\[ \beta = \frac{kl}{x} \]

(2)

where \( \nu = l + 1/2 \), \( \xi_q \) is the \( q \)th zero of the Airy function, \( n_1 \) is the refractive index of the microsphere and \( n_2 \) is the refractive index of the medium surrounding the microsphere.

2.2 Coupling efficiency between the tapered fibre and the microsphere

For the tapered fibre and the microsphere, the degree of overlap of the evanescent fields, arising from the gap between the taper and the microsphere, affects the coupling efficiency [9]. Several parameters are used to characterize this effect and the most important parameters are the coupling quality factor, \( Q_c \), which describes the whispering gallery mode losses related to the leakage into the coupler and the coupling depth of the coupler (or the coupling efficiency).

The factor \( Q_c \) can be approximated as a function of the coupling gap [12], as shown in equation (3)

\[ Q_c = 102 \left( \frac{r}{\lambda} \right)^{\frac{5}{2}} n^3 (n^2 - 1) \left( \frac{4q - 1}{4q + 1} \right) e^{2\gamma d} \]

(3)
where $r$ is the radius of the microsphere, $d$ is the coupling gap, as shown in Figure 1, $\lambda$ is the input light wavelength, $n$ is the refractive index of the microsphere and $q$ is the radial mode number of the whispering gallery mode.

![Figure 1: Schematic diagram of the coupling between the sphere and the fibre taper](image1.png)

3. Experimental setup

3.1 Component fabrication system

Figure 2 shows the schematic diagram of the fabrication system set up at City University for the fabrication of fibre tapers, where both ends of the fibre are clamped on two separate pulling motorized stages. The hydrogen-oxygen gas torch is mounted on the other scanning stage which ensures the uniform heat distribution when it moves along the axis whereas the speed of pulling of the fibre is controlled by the software using LabVIEW interface. Through appropriate calibration of the setting parameters of the motorized components, this provides a mechanism to create tapered fibres with desired waist diameters and Figure 3 shows a typical picture of the tapered fibre fabricated.

![Figure 2: Schematic diagram of the fibre taper fabrication system](image2.png)

To create appropriate microspheres, two steps are usually taken. First the fibre is pulled by using a flame torch to create a tapered end and then the tapered end was melted using an arc fusion splicer to form a microsphere with required diameter and Figure 4 shows a typical example.
3.2 Er microsphere laser setup
Figure 5 shows the setup of an Er-doped microsphere laser, where a 980 nm laser diode is used as a pump source and the microsphere is made from an Er/Yb co-doped fibre and the sphere diameter is ~55 µm. The tapered fibre is drawn from a SMF28 corning fibre with a waist diameter of ~2µm and the laser output is monitored by using an optical spectrum analyzer (OSA).

4. Experimental results and discussions
Figure 6 shows the microsphere laser output captured by the OSA. It is noticeable that with the increase of pump power, the output laser wavelength is shifting towards the longer wavelength side,
which may be due to the complication arising from temperature change, the mode shifting or the gain profile change as the increase of the pumping power.

5. Conclusion
This paper has shown some preliminary results on the use of the microsphere laser for potential gas sensing. An Er doped microsphere laser has been successfully developed using the components fabricated in house, however, the research is still on-going with an aim to create mid-infrared microsphere laser sources for gas sensing.

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