# Characterisation of Er:ZBNA microspherical lasers

B. Shortt,* R. Carey and S. Nic Chormaic
Department of Applied Physics and Instrumentation, Cork Institute of Technology, Cork and Tyndall National Institute, Prospect Row, Cork, Ireland.

## ABSTRACT

We report here on efforts to characterise erbium-doped, heavy-metal fluoride glass microspherical lasers as a function of pump laser parameters, such as wavelength and power, and the temperature of the microsphere. The microspheres are fabricated from a novel material, ZBNA, optimised for its ability to act as a host for erbium and to favour laser emissions in the near infra-red region at 1.56 $\mu$m from the dopant. We work with microspheres that have typical diameters of ~80 $\mu$m. By attaching the microsphere to the tip of a narrow optical fibre a suitable method for manipulating the microsphere within the set-up has been developed. Pump light at 980 nm is coupled into the microsphere through evanescent wave tunnelling and propagates within the sphere in whispering gallery modes. A half-taper fibre is used as the coupling element. Strong green fluorescence at 540 nm has been observed. This indicates that the pump light is efficiently coupled into the sphere and that the alignment of the system is reasonable. We present an introduction to the fabrication of microsphere lasers, half-taper fibres and the physics of whispering gallery modes. In addition, we discuss the suitability of erbium as a lasing material when used in conjunction with the 980 nm pump light. Finally, we discuss our first experimental observations.

**Keywords:** Lasers, microspheres, erbium doped fluoride glass, whispering gallery modes

## 1. INTRODUCTION

As industry strives towards the miniaturisation of telecommunication systems, a demand for a reduction in the size of optical and optoelectronic devices has arisen. This has fuelled interest in developing micron-sized devices as laser sources. One of the more novel lasers developed consisted of dye-doped edible gelatine[1] that could be cut with a knife into a variety of sizes and shapes. There are many different designs of sub-millimetre sized lasers, including microchips, distributed feedback lasers and dielectric microspheres. The first laser action in a solid-state sphere was demonstrated by Baer,[2] using Nd:YAG spheres with a diameter of 5 mm and a lasing threshold of 100 mW. From there, efforts were focussed on reducing pump laser power and lasing was subsequently achieved in neodymium fluoride glass spheres with a threshold of 5 mW.[3] Nowadays, lasing thresholds at microwatt levels have been reached,[4] while, simultaneously, the size of the spheres has decreased dramatically.

The possibility of using micron sized, spherical particles as resonators, has been studied since the early days of lasers. If a microsphere is doped with a sufficient concentration of rare earth ions it creates an active cavity, which acts as both the gain medium and the resonator for laser emission. Work on these cavities has evolved from liquid droplets[5] to solid state microcavities. The idea of using spherical particles for laser emission was first investigated by Garret *et al.*[6] using $CaF_2$ spheres doped with samarium ions. Other work on dye doped ethanol[7] and water droplets[8] has been reported. The main disadvantage of using droplets as microlasers is that the lasing action takes place over the complete surface of the droplet leading to the loss of one of the main advantages of lasers, their directionality. A second drawback arises from the short lifetime of the droplet, which is a limitation for most applications. Subsequently research has progressed to using doped glass spheres,[9] microdisks fabricated by etching,[10] and microrings of semiconducting polymers.[11]

Microdisks are composed of an optically-thin semiconductor layer with a diameter of a few microns. They have a small gain volume and ultra-low threshold. In contrast, microspheres can be made using a number of different glasses, e.g. fluoride,[9] silica[12] and phosphate,[13] and these can be readily doped with varying concentrations of rare earth ions such as

* Brian.shortt@cit.ie; phone 353 31 490 4864; fax 353 21 4904880.

Er, Nd, Tm and Ho. These lasers boast low thresholds due to their small size, resulting in a significant reduction in the pump power required for excitation. An additional advantage is that the fabrication of such devices can be preformed in any standard laboratory.

Mode propagation in circular microlasers is based on multiple total internal reflections (TIR) of light within the structures. These have been termed whispering gallery modes (WGM), a term that has been adopted from the acoustical domain to describe a phenomenon observed early last century by Lord Rayleigh.[14] He noticed that whispers propagate along the dome of St. Paul's Cathedral in London. He interpreted this effect as efficient reflections along the curved walls, which allow a whisper against the wall to be audible on the other side of the dome. He later suggested that such modes of the electromagnetic field would yield some useful applications because of their high quality ($Q$) factors. WGMs in microresonators have attracted a lot of attention in recent years due to this feature and the very low mode volumes of typically a few hundred $\mu m^3$ that can be achieved.[15] $Q$-factors as high as $10^{11}$ have been reported.[16] The development of such microresonators is of interest for both fundamental (e.g. cavity quantum electrodynamics[5,17]) and applied studies (e.g. the development of optical networks[16]). Applications have also been identified in chemical and biological sensing.[18]

In this paper we will first introduce the physics behind the whispering gallery mode propagation within a microsphere. We will then consider methods of efficiently coupling pump light into the sphere by ensuring that mode matching between the pump laser and the microlaser is achieved. Next, we will consider the main methods used to fabricate the spheres and the tapers used for pump coupling. In addition, we will discuss how one can create a microlaser by doping the sphere with erbium ions. When pumped with 980 nm light, the two primary emissions are at 1.5 $\mu$m, which is of interest for the telecommunications industry and sensing applications, and 540 nm. Finally, we'll present the future directions for this work including a full study of the 540 nm emission as a function of pump power and wavelength, and microsphere temperature.

## 2. THEORETICAL CONSIDERATIONS

Light propagation within a microsphere laser is dictated by the behaviour of the whispering gallery modes. A full theoretical analysis of these modes can be found elsewhere.[19] The following section serves as an introduction to this phenomenon and is based on a simple geometrical optics description. In addition, we will provide some insight into the concept of a cavity's quality factor, a measure used to indicate its ability to store light. Finally, in order to achieve efficient pumping of a lasing microsphere, it is imperative that the propagation modes of light in the coupling element match the WGMs within the sphere. The use of quantum tunnelling via an evanescent wave component of the light field is used for this purpose and we will show how one can ensure that the coupling technique satisfies the mode-matching requirements when a half-taper fibre is used as the coupling component.

### 2.1 Whispering gallery modes

Consider a ray of light travelling within a microsphere of radius $r$ and refractive index $N$ (Fig. 1(a)). If the ray strikes the air-glass interface at an angle of incidence greater than the critical angle, TIR will occur. The ray is reflected and strikes the air-glass interface again at the same angle. In the case of large microspheres ($r \gg \lambda$), with zero eccentricity, the light ray will be trapped by this mechanism and can propagate continuously around the inside wall.

This simple geometrical picture can also support the formation of resonances or modes within the sphere. A wave making a single round trip inside the sphere covers a distance of approximately $2\pi r$. If the condition

$$2\pi r = \beta \lambda_s \tag{1}$$

is satisfied, where $\beta$ is an integer and $\lambda_s = \lambda / N$ is the wavelength of the propagating light in the sphere, then a standing wave will occur.

This simple picture is only physically valid for *large* microspheres, that is spheres which possess a large size parameter, $x$, defined as

$$x = \frac{2\pi r}{\lambda} \tag{2}$$

Combining eqns. (1) and (2) we can then state the resonance condition in terms of the size parameter as simply

$$x \approx \frac{\beta}{N} . \tag{3}$$

This condition can also be described by using a photon instead of a ray picture. The momentum $p$ of this photon is given by

$$p = \hbar k = \frac{2\pi\hbar}{\lambda_s} , \tag{4}$$

where $\hbar$ is Planck's constant divided by $2\pi$ and $k$ is the wavenumber inside the sphere. The angular momentum, $\hbar l$, of the photon when it strikes the surface with near glancing incidence is given by

$$\hbar l \approx rp = \frac{2\pi r\hbar}{\lambda_s} . \tag{5}$$

Equating eqns. (1) and (5), we see that the integer $\beta$ is the angular momentum of the photon of unit $\hbar$.

In reality the electromagnetic field patterns set up in a microsphere are far more complicated than the simple geometrical picture presented above. WGMs can be represented by three mode numbers $n$, $l$, and $m$ which represent the radial, equatorial and polar components of the electromagnetic field. Mode number $n$ ($n$ = 1, 2, 3,…) gives the number of maxima in the radial electromagnetic field distribution. Mathematically, this distribution is described by spherical Bessel functions. The fundamental ($n$ = 1) radial mode is depicted in Fig. 1(b). It should be noted that a complete description of the radial component of the WGM must also account for the evanescent tail which extends from the sphere into free space. The second mode number, $m$, describes the variation in the field intensity in the equatorial or latitudinal direction. The variation of field intensity around the equator is sinusoidal in nature. This mode number can take the set of values $m = -l, -l + 1,\ldots, 0,\ldots, l - 1, l$. The final mode number, $l$, describes the field intensity distribution in the polar or longitudinal direction. Theoretical analysis shows that this distribution is described by spherical harmonic functions and can take values $l$ = 0, 1, 2,… The number of maxima present in the polar field distribution is given by $l - |m| + 1$.

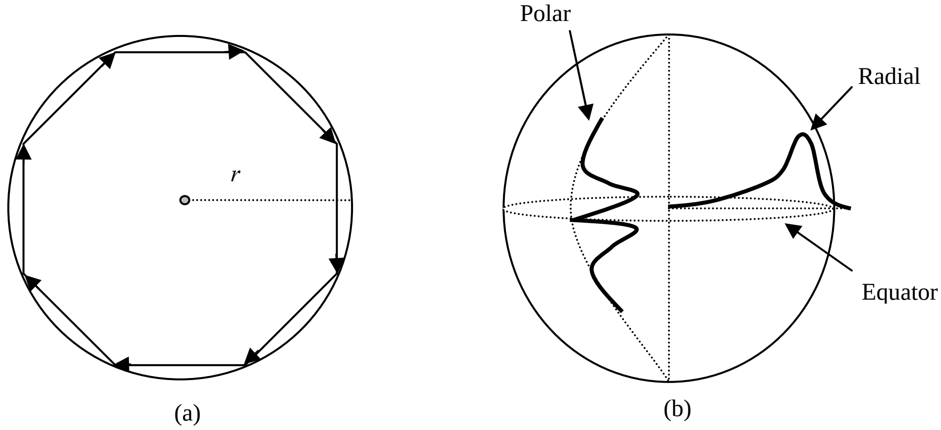


Figure 1: WGM in a microsphere. (a) Ray propagation around the sphere by TIR; (b) The fundamental radial mode $n$ = 1 and the first even ($l - |m| = 1$) polar mode are shown.

In a perfect sphere, modes with the same $l$ but different $m$ values are degenerate and so the mode numbers $n$ and $l$ are sufficient to describe the WGM. However, in reality some ellipticity exists in the sphere which removes this degeneracy. For minimal mode volumes one wants $n$ to be small and $m \approx l$. This ensures that the mode is close to the surface of the sphere and near the sphere equator. In the ray optics picture this represents a ray with the smallest reflection angle and the lowest diffraction losses. This is the fundamental mode of the sphere and has the lowest mode volume and the highest $Q$-factor. It is also worth noting that WGMs are frequently described as morphology dependent resonance modes,[20,21] since their behaviour depends on the refractive index and radius of the sphere.

In order to generate a laser in a microsphere, it is essential that light be coupled into a WGM of the sphere. The spheres of interest for lasing are generally fabricated from silica or fluoride glass doped with rare earth ions (e.g. $Er^{3+}$, $Yb^{3+}$). The modes of the pump light must match the WGMs for efficient pumping to occur. It has been shown[9,22] that there are two reliable methods for achieving this. One technique uses a prism coupler whereby the evanescent wave modes match the WGMs. The other technique relies on coupling via half- or full-taper fibres. The advantage here is the ease of alignment of the system. In addition, the use of fibre tapers is highly compatible with the development of all optical systems as they are smaller in size and easier to incorporate than prism couplers.

### 2.2 Quality factor of a laser

The performance of a resonator is frequently described in terms of its ability to store energy. Microspheres have lower losses than other optical resonators. This leads to long-lived resonances and, hence, quality factors several orders of magnitude higher than for other types of resonators. The $Q$-factor is a measure of the length of time for which a photon can be stored within the cavity. For a microsphere resonator it is roughly equal to the amount of time a ray spends travelling around the cavity without succumbing to a loss process. In an ideal sphere, i.e. one free from losses, the lifetime would tend towards infinity. However, in reality the losses within a microsphere resonator arise due to both internal and external mechanisms. The internal losses result from scattering due to surface roughness and absorption due to impurities within the cavity. The external losses are associated with diffraction and tunnelling, which results in light coupling out of the cavity. Surface scattering can be limited by fabricating smooth surfaces and tunnelling losses can be limited by using spheres with diameters greater than 30 $\mu$m. The $Q$-factor of the sphere also degrades with time as water and other pollutants gather on the surface. Thus, the dominant losses are due to Rayleigh scattering and absorption.

To measure the $Q$-factor of a microsphere laser one can observe the time it takes for the output to decay after the input of a short pulse. An expression for $Q$ is given below[23]

$$Q = 2\pi \frac{\text{Stored energy}}{\text{Energy dissipated in one cycle}} = f \frac{\omega_0}{\Delta\omega}\,, \tag{6}$$

where $f$ is a numerical factor which depends on the definition of the bandwidth, $\Delta\omega$, at resonance $\omega_0$.

### 2.3 Mode matching between a microsphere and taper fibre

In order to effectively couple light into microsphere lasers, the mode pattern of the pump beam must match that of the WGMs within the sphere. This can be achieved via an evanescent wave, which can tunnel into the microsphere. There are many devices available which can be used to achieve this effect, including prisms,[24,25] taper fibres,[24] half-block couplers[26] and angled polished fibre couplers.[27]

In the prism coupling method,[25] a high index prism is brought very close (~0.4 $\mu$m) to the microsphere surface. The pump light is focused onto the surface of the prism. The pumping angle can be changed to achieve total internal reflection within the prism, which results in an evanescent wave beyond the prism's surface. This method ensures that mode matching with the WGMs is achieved. The microsphere is excited by optical tunnelling of the evanescent wave. Different WGMs can be excited by changing the angle of incidence and the wavelength of the pump beam. The distance between the sphere and the prism can be adjusted to optimise the coupling rate. Resonances can be detected as dips in the intensity of the reflected pump beam from the prism, the depth of which indicates the coupling efficiency. The difficulty with this method is that it is bulky and its alignment is extremely non-trivial. The prism coupling method is, however, highly selective, generally exciting a single WGM.

If coupling is to be achieved using tapers or half-tapers, it is imperative that the taper be only a few microns in diameter. Taper coupling provides a simple and potentially compact method of exciting the sphere. However, the tapers are difficult to fabricate and are extremely fragile. Coupling efficiency is very high and depends on the refractive index of the sphere, sphere dimensions, taper fibre dimensions and the relative position of the components. However, in general, more than one mode is excited within the sphere. For this type of coupling one needs to match the propagation constant of the sphere to that of the taper.[28] An expression to determine the propagation constant, $\beta_s$, for the sphere is given by[28]

$$\beta_s = \frac{kl}{x_{nlm}}, \tag{7}$$

where $x_{nlm}$ is the size parameter that corresponds to the $n$, $l$, and $m$ resonance, and $k$ is the propagation constant. The propagation constant for the taper, $\beta_t$, is given by[28]

$$\beta_t^{\,2} = k^2 N^2 - \frac{5.784}{\rho^2}, \tag{8}$$

where $N$ is the refractive index of the sphere and $\rho$ is the taper radius. Fig. 2 presents the plots of $\beta_t$ versus fibre radius for both the pump (980 nm) and lasing (1.5 $\mu$m) wavelengths. Since the taper propagation constant is reasonably close in magnitude for both wavelengths it should be possible to use a single fibre for the pump and lasing light.

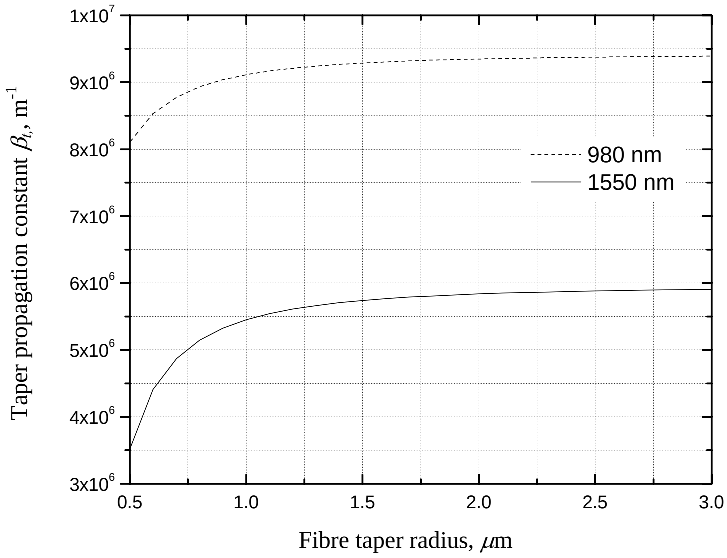


Figure 2: Taper propagation constant as a function of taper radius for both pump (980 nm) and microsphere lasing (1.5 $\mu$m) wavelengths.

## 3. EXPERIMENTAL DETAILS

In this section we will present the set-up being used in our laboratory for characterising the spectral output of microsphere lasers. We are investigation the spectral emissions from erbium-doped ZBNA spheres as a function of pump input at 980 nm. ZBNA is a new heavy-metal fluoride glass (HMFG) that has been developed in France by a group specialising in the creation of novel materials for photonic applications.[29] HMFGs[30] are used for very low loss fibre optics in the near infrared region[31] and commonly used materials in this family include ZBLAN and ZBLA.

ZBNA has been optimised to act as a host material for erbium with lasing at 1.56 $\mu$m. The bulk properties of this material are being investigated simultaneously by our collaborators in ENSSAT, in order to determine its transmission and absorption characteristics. The doping level can be varied within the ZBNA and bulk materials with a range of doping concentrations have been fabricated. In our experiment we are using 0.1% $Er^{3+}$ doping concentration within the ZBNA solid sphere. The excitation of the WGMs is achieved using a 980 nm pump laser coupled via a half-taper fibre with a tip diameter of a few microns.

### 3.1 Microsphere fabrication

There are a number of different techniques which can be used to fabricate microspheres. It is vital that the method adopted minimises contamination, which could reduce the $Q$-factor of the resonator. Some techniques in use include melting the tip of a fibre with a high power laser,[32] via an electric arc[33] or dropping glass powder through a microwave plasma torch.[24]

When melting the tip of a fibre using a high power laser, a length of optical fibre, e.g. erbium-doped fibre, has to be stripped and cleaved. The laser is focussed onto a section of the fibre until it melts. Once the glass passes its melting point surface tension gives it a spherical form. When removed from the heat it solidifies. Spheres of varying diameter can be produced depending on the laser beam focus and this can be controlled further by thinning the fibre before placing it in the beam. The main advantage to this method is that the sphere is already attached to a support allowing easy manipulation and installation into an experiment. However, if the stem is too big this can reduce the $Q$-factor of the sphere by increasing the resonant cavity losses.

A fusion splicer can also be used to produce microspheres.[33] In this technique, fibre is initially etched to achieve very fine tips and it is then placed in a fusion splicer. The ends of the fibre melt due to the applied electric arc when the splicer is switched on. If all the parameters in the splicer are accurately controlled one can get reproducible spherical shapes. The microspheres are relatively easy to retrieve from the splicer and subsequently manipulate by ensuring that the fibre stem remains attached. Sphere diameters in the 100 to 400 $\mu$m range have been achieved using this technique.

Our spheres are made in the Laboratoire d'Optronique of ENSSAT, Lannion using a microwave plasma torch.[24] The torch uses a mixture of argon and oxygen or nitrogen. The plasma is generated using a microwave supply with an oscillator frequency of 2.4 GHz and a maximum power of 2 kW. Fluoride or silica glass is crushed into a powder and is axially injected through the flame. The glass is melted on passing through the plasma flame and surface tension gives the spheres their spherical form. Free spheres are formed and collected several tens of cm beneath the torch. The diameter of the spheres produced varies between 10 $\mu$m and 200 $\mu$m and is largely dependent on powder size. The system can be optimised for different glass materials by changing the ratio of the gases feeding the plasma discharge.

It has also been suggested that wafer based fabrication techniques could be employed to create spheres.[34] By creating structures on a silica wafer and then melting it into a spherical shape, spheres attached to stems could be fabricated. The process would involve oxidation to get a silica layer, which would require a mask according to the shape required and etching while the mask is in place. The driving force behind development of this technique is to increase production rates and the quality of the spheres.

#### 3.1.1 Erbium

In order to observe lasing behaviour, it is essential that the microsphere be doped with a rare earth ion such as erbium. We are using $Er^{3+}$ ions at a very low concentration (~0.1%) within the ZBNA host material. The erbium transitions of interest are shown in a partial energy level diagram in Fig. 3. There are three main wavelengths that can be used to pump erbium and these are 800 nm, 980 nm and 1.48 $\mu$m. We pump using a tunable diode laser operating over the range 975-985 nm. This wavelength range is utilised due to its compatibility with telecommunications components and the fact that it differs significantly from the lasing wavelength of 1.5 $\mu$m, allowing a clear separation of the two components.

Absorption of a laser photon at 980 nm pumps the erbium atom from the ground state $^4I_{5/2}$ to the $^4I_{11/2}$ excited state (lifetime < 1 $\mu$s). From this excited state the atom can either a) undergo non-radiative relaxation to the metastable $^4I_{13/2}$ state (lifetime ~10 ms) or b) absorb a second pump laser photon to enter the $^4F_{7/2}$ excited state – excited state absorption.

In the case of a) the atom can return to the ground state after ~10 ms via the spontaneous emission of an infra-red photon at 1.5 $\mu$m. Alternatively the atom can relax to the ground state via stimulated emission and this forms the basis for 1.5 $\mu$m lasing in the microsphere. The multiphoton process described in b) is a source of possible quenching of the lasing at 1.5 $\mu$m. If the 980 nm pump intensity is too high the two photon absorption rate will lead to efficient population of the $^4F_{7/2}$ state. This state can relax to either the $^2H_{11/2}$ or $^4S_{3/2}$ states and these states further decay to the ground state via photon emissions at 520 and 540 nm respectively.[35] These wavelengths are in the visible green part of the electromagnetic spectrum. The green light can be used as a guide for alignment of the system and can also be studied as a function of the pump parameters. In order to ensure that the 1.5 $\mu$m transition occurs, it is essential to reduce the probability of the green transition by reducing pump power.

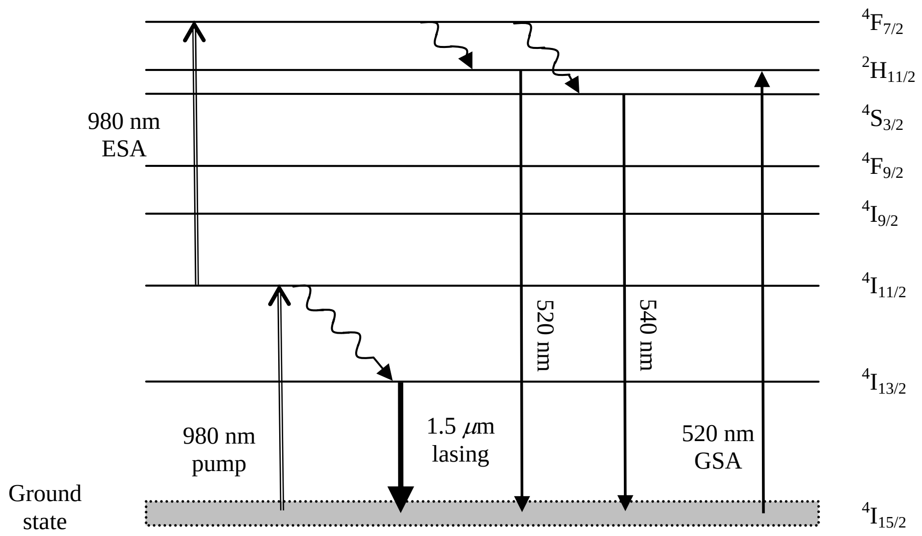


Figure 3: Energy levels and transitions for $Er^{3+}$. The erbium transitions of interest are the pump at 980 nm, the green emission at 540 nm and the IR emission at 1.5 $\mu$m. ESA – excited state absorption, GSA – ground state absorption.

As well as its dependency on pump wavelength, the behaviour of erbium as a gain medium is influenced by the host material. Quartz glass is suitable for applications in the UV as it has good transmission properties in this wavelength region. Fluoride glass has a broad infrared transmission spectrum, e.g. erbium-doped fluoride amplifiers (EDFA) are widely used in telecommunications. Fluoride glasses[36] can absorb rare earth ions such as erbium up to high concentrations and so provide a promising candidate for a compact optical gain medium. These high concentrations have the advantage of allowing efficient pumping, high gain and high efficiency of energy transfer between the ions. Other glasses that can be used include silica and phosphate. Phosphate glasses[37] have attractive properties such as high gain, low concentration quenching and low up-conversion losses.

### 3.2 Fabrication of half-taper fibres

In our experiment we are using a half-taper fibre to excite the Er:ZBNA microspheres. The half-taper is fabricated by pulling standard single mode fibre over a hydrogen-oxygen flame until it breaks. Some of the half-tapers we use have been fabricated using two motorised pulleys to control the rate at which the fibre is stretched. However, we have also found that it is possible to make them by manually pulling the fibre over a flame. This method produces long tips with small tip angles, with typical diameters in the 1-4 $\mu$m range. We have also investigated an alternative method, whereby half-tapers are fabricated using chemical etching,[38] the principle of which is illustrated in Fig. 4. The etchant is composed of 40% ammonium fluoride ($NH_4F$) and 50% hydrofluoric acid (HF), where percentages are given by weight. The fibre is immersed in the solution and a thin layer of silicone oil is placed on top. There is an initial meniscus height on the fibre as shown Fig. 4(a). As the etching proceeds there is an upward pulling force resulting from the surface tension due to the decrease in contact area between the fibre and etchant (c.f. Fig. 4(b)). This means that the meniscus height reduces until the fibre below the oil is etched and a tip is formed c.f. Fig. 4(c). The difficulty with this process is that the timing is quite critical in order to achieve a smooth taper without deformations.

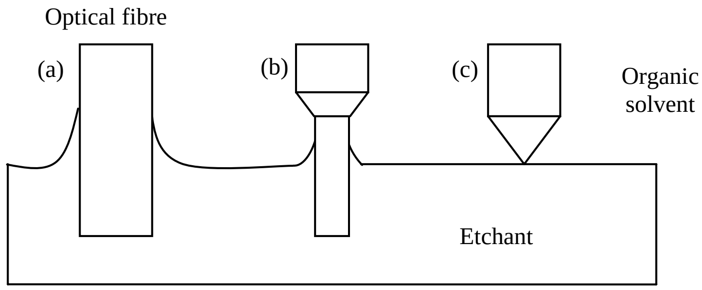


Figure 4: Formation of a taper by chemical etching. (a) The optical fibre is initially placed in the etchant; (b) As the process begins the fibre is etched; (c) Eventually the process self-terminates.

### 3.3 Experimental details

A suitable microsphere is selected using a × 50 magnification on a Nikon microscope. The sphere must be free of defects (e.g. air bubbles, surface dirt) and have a good spherical form in order to ensure WGM propagation. For subsequent handling of the microsphere we glue it onto the tip of a stretched optical fibre with a diameter of ~8 $\mu$m for a sphere diameter ~40 $\mu$m. An image of the sphere/fibre ensemble is shown in Fig. 5. This fibre support is produced by heating it over a small gas flame and manually stretching it until it breaks. The microsphere ensemble is then mounted on a piezoelectric flexure stage for alignment purposes.

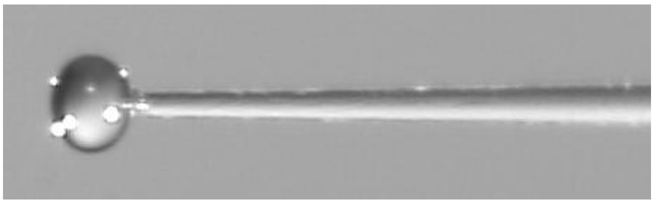

Figure 5: Magnified image of a 40 $\mu$m diameter microsphere attached to an 8 $\mu$m tapered fibre.

The experimental arrangement is presented schematically in Fig. 6. A tunable, 980 nm multimode butterfly diode laser, with a maximum output power of 80 mW is used as the pump. The wavelength can be tuned between 975 nm and 985 nm by changing the diode current and temperature. The pump light is sent through an optical isolator to prevent back reflections into the laser. It then passes through a manual variable attenuator, which enables us to study the lasing characteristics of the microsphere as a function of the pump beam power.

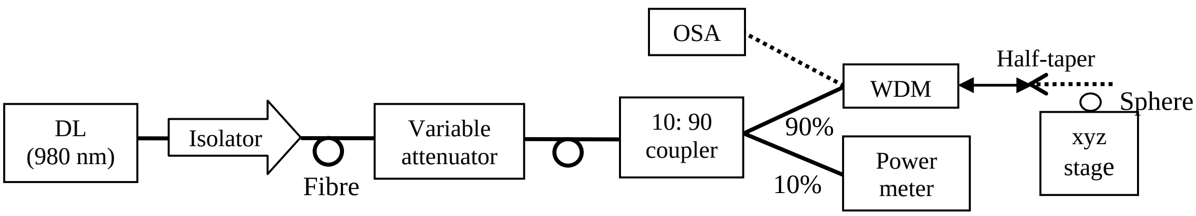


Figure 6: Experimental set-up. Full line indicates 980 nm. Dashed line indicates 1.5 $\mu$m. DL: Diode laser, WDM: Wavelength division multiplexer, OSA: Optical spectrum analyser.

The light next passes through an IDIL 10:90 coupler. A power meter is connected to the 10% channel and this enables us to monitor the pump power at all times. The remaining 90% is used as the primary beam for the experiment and is coupled into the half-taper fibre via a wavelength division multiplexer (WDM). The half-taper is optimised for 1.5 $\mu$m. However, due to the small distances involved, the attenuation of the 980 nm signal is negligible.

Near equatorial modes can be excited by ensuring the microsphere equator is aligned precisely with the half-taper used for evanescent wave coupling. A portion of the pump light is coupled into the microsphere and propagates within it via multiple reflections. Due to the presence of $Er^{3+}$ in the glass, light is reemitted at 540 nm and WGM resonances are established. This is very evident due to the presence of green orbits within the sphere. The fluorescence can be seen with the naked eye and the orbits are visible through a Zeiss microscope connected to a monitor via a CCD camera. The alignment position of the half-taper and microsphere is also displayed on the monitor. We are currently working with a near zero air-gap between the sphere and the half-taper. The eventual aim is to increase the air-gap in order to minimise losses from the sphere thereby improving the $Q$-factor of the ensemble. The presence of the 540 nm emission indicates that weaker 1.5 $\mu$m transitions should also be occurring within the $Er^{3+}$. This behaviour is the focus of our current investigations.

When the system is aligned, the microsphere should emit light at ~1.56 $\mu$m. This light is coupled into the half-taper through the evanescent wave component and is carried back through the system. The light passes through the WDM, which separates out the reflected pump component at 980 nm from the lasing component at 1.5 $\mu$m. The 1.5 $\mu$m laser signal is sent to an Anritsu optical spectrum analyser (OSA) for analysis of its spectral properties.

### 3.4. Future work

A number of avenues remain to be explored within the context of this work. The first is a thorough characterisation of the strong green emission at 540 nm as a function of the pump laser wavelength and power. We will switch between continuous and pulsed mode pumping and monitor the corresponding sphere response by collecting the light on an amplified photodiode. The latter mode should reduce the amount of heating of the microsphere arising from the incident pump light and would also allow us to study wavelength tuning as a function of microsphere temperature.

We are also investigating an alternative optical arrangement to the one presented above. The use of separate tapers or half-tapers for the 980 nm and the 1.5 $\mu$m will allow us to fully analyse the system without significant attenuation of either signal. The use of a full taper for the pump light will also allow us to study the reduction in pump intensity when coupling into the microsphere is achieved, by monitoring the light propagating through the fibre.

Currently, the microspheres we use are supplied by an external source. We now have the facilities in place within our laboratory to fabricate our own spheres using a strongly focussed Synrad $CO_2$ laser, which has a maximum output power of 25 W. This will enable us to work with spheres optimised for our particular needs. We will commence investigating the fabrication of microspheres by focusing the $CO_2$ laser onto a section of standard optical fibre. The use of a 2.5 cm focal length zinc selenide lens will yield a power density of ~3kW/mm$^2$. Once the technique is perfected and we are able to produce spheres with low ellipticity and excellent surface smoothness, we will extend our studies to use highly doped and very highly doped erbium fibre (EDFAs). This will provide the dopant necessary in order to achieve lasing at 1.5 $\mu$m within the microlaser.

Finally, we would like to investigate the feasibility of using the current system as a miniature optical sensor for trace gas detection. Carbon monoxide (CO) has an absorption peak in the 1.5 $\mu$m region and we hope to develop a miniature sensor for detecting trace amounts of CO within a sample gas cell.

## 4. CONCLUSIONS

In this paper, we have presented an introduction to the topic of microsphere lasers with particular emphasis placed on erbium-doped, heavy-metal fluoride glass spheres. Different methods that can be used to fabricate microspheres are also presented. The work undertaken so far has utilised Er:ZBNA microspheres, fabricated by dropping glass powder through a microwave plasma torch. The lasing modes within the microsphere are excited through evanescent wave coupling of a pump beam at 980 nm via a half-taper fibre. The light propagates around the microcavity in the form of whispering gallery modes defined by three quantum numbers. Emissions at 540 nm have been observed as a strong green fluorescence within the sphere. Due to the allowed transitions within erbium pumped at 980 nm, we therefore expect 1.5 $\mu$m lasing to be present and we are currently optimising the system in order to detect this weaker, infrared signal.

## ACKNOWLEDGEMENTS

We wish to acknowledge Patrice Féron and Carole Arnaud, Laboratoire d'Optronique, ENSSAT, France for supplying us with the microspheres for this work and for many insightful discussions. We are also grateful to Norma O'Sullivan and Conneth Hussey from the University of Limerick for providing us with tapered SMF-28 fibre. We thank Alexander Yarovitskiy for his contributions to this work. This work is supported by Science Foundation Ireland project number 02/IN1/I28.


## REFRENCES


1. T. W. Hänsch, M. Pernier and A. L. Schawlow, "Laser action of dyes in gelatin", IEEE J. Quant. Elec. **7**, 45-46, 1971.
2. T. Baer, "Continuous-wave laser oscillation in a Nd:YAG sphere", Opt. Lett. **12**, 392-394, 1987.
3. K Miura, K. Tanaka and K. Hirao, "CW laser Oscillation on both the $^4F_{3/2}$–$^4I_{11/2}$ and $^4F_{3/2}$–$^4I_{13/2}$ transitions of $Nd^{3+}$ ions using a fluoride glass microsphere" J. Non-Crystalline Solids **213** & **214**, 276-280, 1997.
4. S. M. Spillane, T. J. Kippenberg and K.J. Vahala, "Ultralow-threshold Raman laser using a spherical dielectric microcavity", Nature **415**, 621-623, 2002.
5. J. Campillo, J. D. Eversole and H-B Lin, "Cavity quantum electrodynamics enhancement of stimulated emission in microdroplets", Phys. Rev. Lett. **67**, 437-440, 1991.
6. G. Garret, W. Kaiser and W. L. Bond, "Stimulated emission into optical whispering modes of spheres", Phys. Rev. **124**, 1807-1809, 1961.
7. S.-X. Qian, J. B. Snow, H.-M Tzeng and R. K. Chang, "Lasing droplets: highlighting the liquid-air interface by laser emission", Science **231**, 486-488, 1986.
8. A. Biswas, H. Latifi and R. L. Armstrong, "Time resolved spectroscopy of laser emission from dye doped droplets", Opt. Lett. **14**, 214-216, 1989.
9. F. Lissillour, P. Féron, N. Dubreuil, P. Dupriez, M. Poulain and G. M. Stéphan, "Erbium-doped microspherical lasers at 1.56 $\mu$m", Electron. Lett. **36**, 1382-1384, 2000.
10. S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton and R. A. Logan, "Whispering gallery mode microdisk lasers", App. Phys. Lett. **60**, 289-291, 1992.
11. Y. Kawabe, Ch. Spiegelberg, A. Schülzgen, M. F. Nabor, B. Kippelen, E. A. Mash, P. M. Allemand, M. Kuwata-Gonokami, K. Takeda and N. Peyghambarian, "Whispering gallery mode microring laser using a conjugated polymer", Appl. Phys. Lett. **72**, 141-143, 1998.
12. F. Treussart, N. Dubreuil, J. Knight, V. Sandoghdar, J. Hare, V. Lefevre-Seguin, J. M. Raimond and S. Haroche, "Microlasers based on silica microspheres", Ann. Telecommun. **52**, 557-568, 1997.
13. M. Kuwata-Gonokami, K. Takeda, H. Yasuda, and K. Ema, "Laser emission from dye-doped polystyrene microsphere", Japanese J. Appl. Phys. **231**, L99-L101, 1992.
14. Lord Rayleigh, "Whispering gallery modes", Phil. Mag. **20**, 1001-1004, 1910; *idem* "The problem of the Whispering Gallery", *Scientific Papers Vol. 5*, 617-620, Cambridge University, Cambridge, 1912.
15. W. von Klitzing, E. Jahier, R. Long, F. Lissillour, V. Lefèvre-Seguin, J. Hare, J-M. Raimond and S. Haroche, "Very low threshold green lasing in microspheres by up-conversion of IR photons", J. Opt. B: Quantum Semiclass. Opt. **2**, 204-206, 2000.
16. T. Bilici, S. Isci, A. Kurt and A. Serpengüzel, "Microsphere based channel dropping filter with an integrated photodetector", IEEE Photon. Technol. Lett., **16**, 476-478, 2004.
17. F. Treussart, J. Hare, L. Collot, V. Lefèvre, D. S. Weiss, V. Sandoghdar, J. M. Raimond and S. Haroche, "Quantized atom-field force at the surface of a microsphere", Opt. Lett. **19**, 1651-1653, 1994.
18. *Optical Processes in Microcavities,* R. K. Chang and A. J. Campillo, World Scientific, Singapore, 1996.
19. S. Schiller and R. L. Byer, "High-resolution spectroscopy of whispering gallery modes in large dielectric spheres", Opt. Lett. **16**, 1138-1140, 1991.
20. S. Schiller, "Asymptotic expansion of morphological resonance frequencies in Mie scattering", Appl. Opt. **32**, 2181-2185, 1993.
21. G. Griffel, S. Arnold, D. Taskent, A. Serpengüzel, J. Connolly and N. Morris, "Morphology-dependent resonances of a microsphere-optical fiber system", Opt. Lett. **21**, 695-697, 1996.

22. F. Lissillour, D. Messager, G. Stéphan and P. Féron, "Whispering-gallery-mode laser at 1.56 $\mu$m exicted by a fiber taper", Opt. Lett. **26**, 1051-1053, 2001.
23. R. Baltz, "Photonic structures: atoms, molecules, wires and crystals", in *Spectroscopy of systems with spatially confined structures*, NATO Science Series II Vol. 90, di Bartolo, Baldassare, Springer, 2002.
24. P. Féron, "Whispering gallery modes as laser sources- a short review", in *Quaderni di optica e fotonica, special issue: Photonics & Optoelectronics*, Winter School, Trento, 2001.
25. L. Collot, V. Lefèvre-Seguin, M. Brune, J. M. Raimond and S. Haroche, "Very high-*Q* whispering-gallery mode resonances observed on fused silica microspheres", Europhys. Lett. **23**, 327-334, 1993.
26. V. S. Iltchenko, X. S. Yao and L. Maleki, "Simple fiber optic coupling of microsphere resonators", NASA Tech Brief **25**, JPL New Technology Report NPO 20319, 2001.
27. V. S. Iltchenko, X. S. Yao and L. Maleki, "Pigtailing the high-*Q* microsphere cavity: a simple fiber coupler for optical shispering gallery modes", Opt. Lett. **24**, 723-725, 1999.
28. J. C. Knight, G. Cheung, F. Jacques and T. A. Birks, "Phase-matched excitation of whispering gallery mode resonances by a fiber taper", Opt. Lett. **22**, 1129-1131, 1997.
29. M. Mortier, M. Génotelle, G. Patriarche, "Rare earth doped transparent glass-ceramics", presented at Journée Nanoparticule, Paris, October 2000.
30. M. G. Drexhage, "Heavy metal fluoride glasses", *Treatise on Materials Science and Technology, Vol. 26: Glass IV*, M. Tomozawa and R. H. Doremus, 151-243, Academic, New York, 1985.
31. C. H. L. Goodman, "Devices and materials for 4 $\mu$m-band fiber optical communication", Solid State Electron. Devices **2**, 129, 1978.
32. T. J. Kippenberg, S. M. Spillane, B. Min and K. J. Vahala, "Theoretical and experimental study of stimulated and cascaded Raman scattering in ultra-high *Q* optical microcavities", IEEE J. of Selected Topics in Quant. Electron. **10**, 1219-1228, 2004.
33. J. P. Laine, B. E. Little, D. R. Lim, H. C. Tapalian, L. C. Kimerling and H. A. Haus, "Planar integrated wavelength-drop device based on pedestal antiresonant reflecting waveguides and high-*Q* silica microspheres", Opt. Lett. **25**, 1636-1638, 2000.
34. J. P. Laine, *Design and Applications of Optical Microsphere Resonators,* Ph.D. Thesis, Helsinki University of Technology, 2003.
35. J. Y. Allain, M. Monerie and H. Poignant, "Tunable green upconversion erbium fibre laser", Electron. Lett. **28**, 111-113, 1992.
36. Z. Meng, j. Kamebayashi, M. Higashihata, Y. Nakata, T. Okada, Y. Kubota, N. Nishimura and T. Teshima, "1.55 $\mu$m Ce-Er_ZBLAN fiber laser operation under 980 nm pumping: Experiment and simulation", IEEE Photon. Technol. Lett. **14**, 609-611, 2002.
37. R. Wu, J. D. Myers, M. J. Myers and C. Rapp, "Fluorescence lifetime and 980 nm pump energy transfer dynamics in erbium and ytterbium co-doped phosphate laser glasses", in *Proc. of SPIE #4968: Solid-state lasers XII*, R. Scheps, 11-17, San Jose, 2003.
38. P. K. Wong, T.-H. Wang and C.-M. Ho, "Optical fiber tip fabricated by surface tension controlled etching", in *Proc. of Solid-State Sensor, Actuator and Microsystems Workshop*, Hilton Head, 2002.