Optical fibres for sensors

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ABSTRACT

Optimisation of optical fibre design to fully realise the potential of optical sensing systems is discussed. In particular, waveguide geometry and host glass composition are discussed with reference to specific sensor applications.

1. INTRODUCTION

Silica based fibres have many features which make them potentially attractive for sensing applications including light weight, small size, strength, flexibility, chemically passive nature and insensitivity to electromagnetic interference. However optical fibre sensors are not cheap and will not be introduced unless they provide a more economic solution or performance not realisable by conventional methods.

Considerable scope exists for optimising the properties of silica fibres for sensor applications either by modifying the waveguide geometry or by altering the host composition. A few special fibres are currently commercially available of which the polarisation maintaining and rare-earth ion doped structures are the most widely known. The first is widely employed as an intrinsic sensor; the gyroscope, whilst the latter is most used as an active, laser medium and can be employed as a laser source for sensor systems.

The fibre current sensor is potentially attractive owing to its inherent safety in high field environments. Both host and geometric optimisation are discussed for maximum sensitivity and environmental stability. Distributed gratings in fibres are now commonly fabricated with high extinction ratios and narrow linewidths and have great potential as distributed sensors of, for example, temperature or strain. Rare-earth ion doped fibres offer potential as both passive or active distributed sensors but, to date, their greatest potential is as lasers offering application specific performance.

The pace of development is increasing as materials research is intensified and a number of fibre designs for specific applications have been developed. Waveguide geometry and host composition design criteria for optimised performance are described here for a selection of fibre sensors and laser sources to indicate the potential of fibre design.

2 WAVEGUIDE GEOMETRY

2.1 Fibre current sensor

The fibre current sensor based on a modified waveguide structure is presented as an example of the potential of novel geometries[1].

Fibre current sensors consist of a number of fibre coils wound around a current carrying conductor. By virtue of the Faraday effect the current flow induces a rotation of the plane of polarisation of the light travelling along the fibre. The rotation measured depends on the magnitude of the current, the number of fibre turns and the Verdet constant of the material whilst the measurement bandwidth is determined by the transit time of light through the coil. The problem central to the development of a practical device is that of linear birefringence in the fibre invariably present as a result of intrinsic manufacturing imperfections or bend and pressure induced birefringence. This birefringence dominates any Faraday induced rotation in conventional fibres. In a practical device current induced circular birefringence (rotation) should swamp packaging induced linear birefringence. This may be achieved by introducing intrinsic circular birefringence or by increasing the Faraday rotation[2], a form of circular birefringence to swamp any linear effects.

Both approaches have been tested and currently the circularly birefringent fibre performs best. The intrinsic loss of high Verdet constant fibres tends to be high (0.3dB/m) so compromising their sensitivity. A figure of merit for maximum current sensitivity, the ratio of Verdet constant to fibre loss has been developed[3] and it is clear that, for the optimum length silica remains superior. However, for high bandwidth applications the use of high Verdet constant glasses is potentially advantageous but, to date, packaging and form birefringence tend to limit performance although in principle, the use of zero-stress optics coefficient glasses may overcome this drawback.

The spun elliptically birefringent fibre[4] (SEB) is the most robust and practical of the designs considered[5-7] to date. SEB fibres are prepared by spinning a highly linearly birefringent fibre during the draw process to impart a rapid, built-in rotation of the fibre birefringent axis. By introducing a large net elliptical birefringence a compromise can be reached between polarisation holding (and hence packaging insensibility) and the electric current response of a true circularly birefringent fibre. These compromises, and practical fabrication problems, are discussed for production of an optimised fibre.

Expressions for elliptical beat length, L_p^{1}, and maximum current sensitivity, S, relative to an ideal, circularly birefringent fibre, can be derived[8] from the Jones matrices describing the net birefringence of the spun fibre and Faraday rotation per unit fibre length and are summarised graphically in Figure 1. The actual value of fibre sensitivity found in practice depends on the optical configuration used but here S represents the best case. The normalized elliptical beat length and relative current sensitivity for the fibre are plotted in Figure 1(a) and (b) as a function of the ratio of the spin pitch L_T to unspun linear beat length L_p. To make the fibre insensitive to external packaging effects the elliptical beat length L_p must be as short as possible. From Figure 1(a) it is clear that this is achieved by choosing a starting preform with short unspun linear beat length L_p and then selecting a large ratio of spin pitch to unspun linear beat length. However, this ratio cannot be increased indefinitely as the effect is a large decrease in the relative fibre current sensitivity (Figure 1(b)). The decreased sensitivity results because the ellipticity of the eigenmodes of the fibre becomes greater and approaches that of a high linearly-birefringent fibre (i.e., linearly polarized modes) which has a very small response to current. A compromise between the two parameters must be chosen to obtain as short an elliptical mode beat length as possible without seriously reducing the sensitivity. An optimized fibre might have a spin pitch approximately equal to the unspun linear beat length, and is quasicircularly birefringent with $L_p^1 \approx 4.2L_p$ with relative fibre current sensitivity S around 80 per cent (see points marked on Figure 1(a) and (b)). A typical unspun bow-tie preform has a fibre beat length of 1mm, so a spun fibre having an elliptical beat length of 4.2mm will result. This degree of elliptical birefringence is very high and sufficient to allow a bend radius as small as 5mm, making the fibre attractive for short length, high bandwidth applications.

To achieve a spin pitch of 1mm fibre must be drawn slowly whilst the preform is spun rapidly. In practice a spin twist rate of ~2,000rpm is employed with a fibre drawing speed of only a few metres per minute. At such low speeds considerable care is required to ensure the quality of uv cured acrylate coating is maintained and the core is not exposed to high levels of uv light which induce excess loss. The high spin rates require a perfectly straight precursor preform in order to minimise oscillations in the preform tip position which will adversely affect fibre yield. Further, accurate control of fibre drawing temperature and tension are essential. Nevertheless lengths of several hundred meters can be drawn with accurate control of diameter and pitch.

High performance devices with low temperature sensitivity (0.05%/°C) have been demonstrated in a number of configurations. Typical performance for the SEB fibre current sensor is shown in Figure 2 where the current sensitivity is plotted as a function of bandwidth (or length). The curves are plotted for two realizable coil diameters of 10 and 100mm and assuming a practical fibre length limit of 100m, which corresponds to 3,200 turns of a 10mm diameter coil. It is clear that, in the low-frequency region (<300 kHz), the fibre length is limited to 100m by practical, not bandwidth considerations. The minimum detectable current is limited by detection shot noise and thus increases with $(\text{bandwidth})^{1/2}$. Typically for a 1kHz measurement bandwidth a maximum sensitivity of 100μA rms is obtained for a 10mm coil. For higher frequencies (1-100MHz) the sensor is still detection shot-noise limited but, since the maximum fibre length has to be reduced to cater for the increased bandwidth, the minimum detectable current increases with (bandwidth)$^{3/2}$. Thus, for a 10MHz bandwidth a maximum sensitivity of 0.3A rms is projected for a 10mm coil. Above 100 MHz the minimum detectable current increases with (bandwidth)$^{5/2}$, since the detection noise is now dominated by the FET channel noise in the preamplifier.

The environmental robustness of a 100 turn prototype sensor has been assessed and found to have a measurement repeatability of ±0.5% and a temperature drift of 0.05%/°C; a consequence of using birefringent fibre. These current sensor are insensitive to external loading and can be wound as small as 13mm in diameter with only a 1 per cent reduction in sensitivity. The fibre is also found to be ~40dB less vibration sensitive than conventional fibre. The ability to wind small fibre coils while retaining high current sensitivity allows short fibre lengths to be used and high bandwidth are therefore possible. Typical performance gives a maximum current sensitivity of 1mA rms $Hz^{-1/2}$ and a large signal response of 450A rms, a dynamic range of 113dB. With minor improvements, a maximum sensitivity of 100μA rms $Hz^{-1/2}$ and dynamic range of 140dB might be reached and compact all-dielectric current sensors with milliampere sensitivity in the megahertz range can be projected.

2.2 Optical fibre gratings

Three main narrowband (optical fibre) filter types have emerged, with quite different characteristics. These are the fibre relief grating[9], photorefractive Bragg grating[10] and the miniature fibre Fabry-Perot[11] (FFP). Spectral filters consisting of concatenated twin-core fibre have also been demonstrated[12]. Extinction ratio and filter bandwidth are strongly dependent on waveguide geometry, the separation and refractive indices of the two cores. The relief grating and FFP are also modified waveguide structures whilst the photorefractive Bragg fibres rely on glass composition to allow a large, and stable refractive index change to be generated in the fibre core. Also, for pure simplicity and low cost, the rare-earth-doped fibre absorption filter[13] (described below) is hard to match.

2.2.1 Fibre Relief Grating Filters

So called because they apply a physical corrugation on the side of the fibre, fibre relief gratings are made by polishing the fibre cladding to obtain access to the core evanescent field, or employing a D-section fibre. Photoresist is then applied and exposed holographically using a short-wavelength laser. A grating is then etched into the fibre using either a dry or wet process. A high-index layer is then normally applied to "lift" the field and optimise its interaction with the grating corrugations.

Fibre relief gratings act either as a narrowband Bragg reflector, or as a band edge filter[14] in transmission. The latter characteristic is caused by radiation through the grating of wavelengths shorter than the Bragg-resonance, while longer wavelengths are transmitted. Reflectivities as high as 95 per cent with a bandwidth between 25 and 1,800GHz have been reported[15]. Excess losses are (<0.5dB) and limited tunability (3nm) can be obtained by temperature tuning or changing the index of the grating overlay. This process is suitable for all fibre compositions but has been superseded by the photorefractive Bragg grating which is more easily written.

2.2.2 Photorefractive Bragg Gratings

An exciting and relatively recent development is the technique of directly writing photorefractive Bragg gratings within the core of a single-mode fibre[10]. An interference pattern of ultraviolet light at around 240nm is focused onto the core of a germanium-doped silica fibre. After exposure for a few minutes, or even a single pulse, a distributed Bragg reflector is created at a wavelength corresponding to the periodicity of the interference pattern. Using this transverse holographic technique, photorefractive gratings can be written at any wavelength and reflectivities in excess of 99% have been demonstrated[16]. The origin of the effect is the subject of much controversy, with several theories available[17]. There appears to be agreement that it is associated with GeE' centres within the core which absorb strongly at 240nm but writing of the gratings is accompanied by an increase in absorption of only 0.2 per cent at 1.55μm. Predictions of refractive index change at wavelengths far from the GeE' absorption band based on colour centre populations are two orders of magnitude smaller than the observed index changes. The colour-centre model should however be useful for calculating the induced space charge fields suspected to give rise to second-harmonic generation in optical fibres. Comparisons between as-pulled and annealed fibre suggest that the observed index changes may be predominantly due to compaction of the glass, the UV or green/blue light triggering stress relief in the glass by bond breakage. This mechanism may also explain the birefringence that is induced parallel to the exposing optical electric field. A simple model for changes in guided phase index with core radius yields ΔN_{eff} $\sim 10^{-4}$ for several tens of microstrain at 1550nm.

Unlike fibre relief gratings, photorefractive gratings act as a bandstop filter, reflecting the stopped light. Reflection linewidths of 20-100GHz are obtainable and the filters exhibit limited tunability (2nm) using either temperature or strain[18]. The main appeal of photorefractive grating filters is the ease with which they can be made, their very low loss and the non-invasive nature of the fabrication process.

2.2.3 Miniature Fibre Fabry-Perot Filters

These devices have been available for a number of years, but have recently come to prominence with the development of widely-tunable commercial devices. Several configurations are possible, the most popular being to deposit highly-reflective multi-layer dielectric mirrors on the ends of a short (<2mn) stub of fibre which is then glue-spliced between fibre pigtails. Tuning is achieved by piezo-electrically stretching the short fibre length, which incorporates a gap for this purpose. The inclusion of a fibre waveguide within the Fabry-Perot resonator is crucial, since it prevents beam walk-off and allows a high-finesse (>100) to be achieved in a compact, robust device.

FP Filters differ from grating filters in that they have a bandpass characteristic, reflecting the stopped light. In common with all Fabry-Perots, they exhibit multiple passbands, with typical bandwidth of 1-100GHz and a free spectral range (FSR) of 100-10,000GHz has been demonstrated. Excess losses are <3dB and tunability over one or more FSR is possible[19].

Photorefractive Bragg gratings are preferred for ease of writing and high performance, but are most successfully written in hosts containing GeO_2. Photo-induced refractive index changes in other silica-based optical fibre compositions, e.g Al_2O_3-SiO_2 are negligible. However it is found[20] that the addition of ~10,000ppm Ce^{3+} to the glass causes large index changes (~10^{-4}) under uv excitation. Similar effects have been observed[21] in heavily Eu_2O_3 doped phosphate glasses. The mechanism has not been fully explained and it is clear that the potential for grating formation has not yet been fully realised in fibres doped with metal ions.

3 MODIFIED MATERIALS

Many multicomponent glasses exhibit large nonlinear effects and can be drawn into single mode optical fibre via the rod-in-tube technique[22]. Features of particular interest include $\chi^{(2)}$, responsible for second harmonic generation, parametric interactions etc.[22] and $\chi^{(3)}$ responsible for the optical Kerr effect. Further, the host may be optimal for active, laser ions, allowing large emission cross sections and low concentration quenching, leading to, for example, efficient Q-switching (see below). However, it is the advent of rare-earth ion doping of conventional optical fibres[23] which has led to many developments in sensors and devices. This class of material offers many of the advantages of multicomponent glasses whilst retaining the practicality of, and compatibility with, silica. Nevertheless, many devices based on low phonon energy glasses such as ZBLAN have been demonstrated for efficient operation of systems which are dominated by non-radiative decay in silica. The 1.3μm amplifier[24] employing Pr^{3+} doped ZBLAN is currently the most attractive of this class although upconversion laser[25,26] and longer wavelengths (>2μm) systems (see, for example, reference 27) have attracted interest.

Passive effects demonstrated in rare-earth ion doped silica based fibres include photorefractive sensitivity as outlined above and optical filters using the intense narrow absorption bands arising from electronic transitions with the ion. Changes in absorption and emission spectra or decay time arise with temperature due to thermal population of the energy levels so heavily doped fibres may be employed as sensitive temperature monitors. Examples of the range of devices are described here.

The most successful fibre devices to date have been the active laser systems. The combination of waveguide geometry and rare-earth ion doped gain medium has proved particularly powerful with many totally new laser wavelengths demonstrated (for a recent review see reference 28). However, for sensor applications the potential for tunability and high power pulsed operation are most attractive, in for example remote gas sensors or distributed systems respectively. Examples of fibre designs for high performance laser operation in configurations suitable for sources in sensor systems are described here.

3.1 Fibre filter

This is the most straightforward of rare-earth ion doped fibre devices[13] and relies on the strong spectral variation in attenuation in the fibre due to the presence of the dopant ion. These absorption bands are intense but narrow and as a demonstration of the high extinction ratio achievable for small wavelength separations a length of Ho^{3+} doped fibre has been used to detect the anti-Stokes spontaneous Raman scattering signal from the pump wavelength, a differential intensity of ~10^7. The rejection ratio at a given wavelength is simply determined by the choice of dopant ion and dopant concentration or length of filter fibre spliced onto the output end of the fibre under test. The transmission of 633nm pump light and the signal generated on passing through 20m of Raman generating fibre and 7m of filter fibre are shown in Figure 3. The edge of the spontaneous anti-Stokes scattering is seen to dominate, indicating that transmission of the pump is around $3*10^8$ below the input level, without adversely affecting the Raman signal despite a wavelength separation of only 17nm.

3.2 Temperature sensor

3.2.1 Absorptive sensor

Changes in absorption spectra of metal ions occur with temperature as Stark components of the ground state energy level become populated according to the Boltzmann principle. Thus increased absorption on the long wavelength end of an absorption band can be correlated with temperature[29]. The change at 904nm for a GeO_2-SiO_2 core fibre doped with 5ppm Nd^{3+} has been determined to be linear over the range 100°C to -50°C with a sensitivity of 0.2%/°C. The upper limit is imposed by degradation of the acrylate fibre coating. The lower limit is determined by baseline loss, typically a few dB/km compared with 50dB/km absorption in this fibre at 904nm and 0°C. Nd^{3+} was chosen for its high temperature sensitivity at a convenient wavelength, but an extensive analysis of doped fibres[30] suggests that, at the operating wavelength of most commercial optical time domain reflectometry systems Cu^{2+} may be a more appropriate dopant.

The low dopant concentrations required for distributed sensing over long lengths and practical temperature ranges limit the spatial and temperature reduction achievable. Further, fluctuations in doping level will further limit measurement accuracy but early trials demonstrated performance of 2°C and 15m resolution over 140m.

An alternative approach is to employ heavily doped multimoded fibres as multiple point sensors[31]. An aluminosilicate core fibre of 0.2NA and 7.5wt% (27,000ppm) Nd^{3+} has been prepared by solution doping[32], giving an absorption of 3.8dB/cm at 904nm. Such fibres allow resolutions of a few centimetres and less than 1°C to be achieved in a multiple point configuration.

3.2.2 Fluorescence sensor

This sensor relies on a reduction in 1/e emission decay time with increasing temperature which is found to be linear[31] for an aluminosilicate sample doped with 3.5wt (18,400ppm) Nd^{3+} corresponding to a sensitivity of 0.25μs/°C. The maximum dopant concentration is limited by concentration quenching[33] which causes a reduction in decay time. Although a reduction in lifetime with increasing concentration is recorded in aluminosilicate core fibres no fast decay component of the type found in germanosilicate core fibre is seen, suggesting aluminosilicates behave as multicomponent glasses with uniform dopant incorporation.

3.3 Fibre Lasers

The powerful combination of gain medium and waveguide geometry allows a wide range of laser sources to be constructed over an extensive wavelength range[28] with cw room temperature lasers having been demonstrated at wavelengths ranging from the blue to around 3μm. Laser diode pumping is often possible due to the high power densities in the fibre core. Numerous fibres laser geometries have been constructed, in lengths ranging from a few millimetres to kilometres and fibre technology is sufficiently advanced that circuits can be manufactured for specific applications (a review is given in reference 34). These features, in conjunction with their simple construction and thermal stability, make fibre lasers practical and robust sources.

Linewidths of a few tens of kHz are obtained from ring laser cavities with integrated Fabry-Perot filters[35] whilst a figure eight combination leads to the generation of soliton pulses[36]. Conversely, by careful configurational and host design, stable broad bandwidth superfluorescent sources at 1.55μm and 1.06μm have been demonstrated[37,38] for use in gyroscopic applications.

Three examples are given here to indicate the range of designs achievable for use in sensor systems; a Q-switched source producing short high power pulses for OTDR, a tunable narrow linewidth laser for remote methane sensing and a high power cw single mode source giving extremely high output power densities.

3.3.1 Q-switched source

Q-switching of fibre lasers provides a means whereby the low CW power output from an inexpensive laser diode (used as a pump source) can be converted to high-power, short pulses suitable for use in ranging, OTDR and time-multiplexed fibre sensor systems. For a number of these systems the pulse duration sets the spatial resolution limit and hence short pulses of high power are required. Q-switched, laser diode pumped Nd:YLF lasers have been developed for such applications, providing Q-switched pulses as short as 2.7ns with 1.5kW peak power using a 200mW laser diode pump. Use of an amorphous host and fibre geometry gives[39] tunable operation over 40nm, around 1.053μs, 2ns pulses of peak powers in excess of 1kW and repetition rates up to 1kHz, for an absorbed pump power of only 22mW at 810nm. These high powers and short pulse durations have been obtained by use of a special, high-gain neodymium-doped fibre and an electro-optic Q-switch as the modulator element. A heavily Nd^{3+} doped (1wt%) phosphate host is employed to give high emission cross sections and hence high gain efficiency whilst the relatively high dopant concentration of the fibre means that only a short fibre length is required to absorb the pump and this allows relatively short cavities to be constructed. With a high gain amplifier and a short cavity round-trip period, the net gain per unit time (dB/ns) experienced by signal photons in the cavity after Q-switch opening can be very high, even when large values of output coupling are used. This property enables short duration pulses to be obtained in the Q-switched configuration when a fast modulator is used as the Q-switch. Furthermore, using relatively high values of cavity output coupling allows efficient cavity energy extraction to be obtained by minimising the effect of unwanted cavity intrinsic losses.

The typical laser configuration is shown in Figure 4. A 25mm length of Nd^{3+}-doped phosphate fibre was employed and a dichroic dielectric coating with >99% reflection at 1.053μm and >95% transmission at 810nm was applied to one end, while a 1mm thick glass slide was bonded with index-matching adhesive to the other in order to displace the 4% Fresnel reflection from the waveguide end. This reflection thus occurs at a position where the beam is divergent and this reduces feedback into the amplifying fibre, so preventing premature oscillation of the high gain laser (typically 40dB round trip gain). An intro-cavity lens collimates the fibre output onto a 30% reflection mirror, providing the laser output and round-trip feedback. A 50mm long electro-optic, integrated (including polariser) Q-switch is used to modulate the cavity loss with extinction of >500:1 for 3.2kV applied voltage, with <1ns switch time capability. Although compact, the modulator still formed the major component in the overall cavity length (11cm). Typical results are shown in Figure 5. A 100mW single stripe laser diode operating at 810nm was employed to achieve these results, indicating the practical potential of this fibre laser configuration. Further, the reported tuning range of 40nm was achieved simply by replacing the output mirror with a reflection grating.

3.3.2 Tunable fibre laser

A tunable laser source is an attractive high-intensity source for high resolution spectroscopy. Such a source can be employed for the optical detection of gases by scanning it through one or more absorption lines of the gas[40]. Previously, semiconductor diode lasers have been demonstrated as possible sources for this application, but it has generally proved difficult to achieve high-yield manufacture of semiconductor lasers having a precise emission wavelength. However, rare-earth ions incorporated into amorphous media, eg, silica based optical fibre, exhibit broad linewidths absorption and emission due to inhomogeneous broadening. Further, laser emission can be tuned by incorporating a photorefractive grating in the laser cavity.

Rare-earth ion emission spectra are host sensitive thus the wavelength dependence of threshold shows a strong glass dependence. Data[41] are presented in Figure 6 for the three level system Tm^{3+} which exhibits both exceptionally broadband emission, ~300nm around 1700nm, and strong host sensitivity of emission. Further, broad absorption linewidths are advantageous for semiconductor laser diode pumping since only small (~10%) penalties in laser threshold occur over deviations of several nanometres from the optimum pump wavelength[40].

For use in gas sensing the laser is required to be tuned through an absorption line thus a laser cavity of conventional design is employed with an integral fibre Bragg grating used as the tuning element. For the detection of methane the emission is tuned through the P branch in the $2\nu_3$ absorption spectrum, around 1684nm. A dichroic mirror is butted to one end of the active fibre with a fibre photorefractive grating at the other. Stretching the fibre by heating with a Peltier unit tunes the grating reflection and hence the laser emission wavelength, as shown in Figure 7. Laser linewidths of less than 0.1nm are readily achieved (see insert). To demonstrate gas sensing the transmission through a cell containing 2.5% CH_4 in air is normalised to transmission through the cell when filled with N_2. Although the grating employed in this experiment was relatively poor (60%) a change of approximately 50% in normalised transmission is reported. An improved sensitivity is anticipated with better grating efficiencies and fully optimised laser cavity.

3.3.3 Cladding pumping

Careful combination of composition and geometry allows high power diode arrays sources to be exploited for high power cw single mode laser output[42]. The waveguide geometry, shown in Figure 8, typically comprises[43] a heavily rare-earth ion doped core (eg. 3wt% Nd^{3+}) which is located centrally in a rectangular, highly multimoded inner cladding waveguide into which pump light is injected. This is clad with a third material to give a high numerical aperture and circular fibre cross section. The inner cladding is designed to match the large diode diffraction angle and emitting area, whilst minimising the core/inner cladding area ratio, thus optimising the pump absorption in the core and minimising the laser threshold.

Multicomponent glass configurations have proved most successful to date because high doping levels, the required NA's and geometry can be achieved in an all-glass structure. Fibre losses tend to be high (0.1dB/m) so limiting length and requiring dopant concentrations of many wt%. Silica fibres offer the potential of longer devices due to lower outer waveguide losses (0.01dB/m) and hence reduced concentration quenching in the core but the silicone rubber or plastic outer cladding currently used is more difficult to handle.

Cladding pumped lasers and power amplifiers operating at 1.06μm and 1.535μm have been demonstrated. The Yb^{3+}/Er^{3+} codoped energy transfer configuration[44] has been shown to be a practical route to achieving low laser thresholds and high efficiency in the three level Er^{3+} system[45]. However, to date the most impressive results have been achieved in Nd^{3+} doped systems. Performance is comparable to that of the conventional geometry[43] but owing to the efficient use of high power diode arrays 4W cw single mode output at 1.06μm has recently been demonstrated[46], corresponding to power densities of order TW/m^2.

4. CONCLUSION

The optical fibre is shown to be substantially more versatile than just a passive light conduit. Devices based on passive sensitivity to specific measurements have been demonstrated and high performance tailor made active devices using all fibre circuitry are now under development as sources for senors systems.

Fibre design, both compositional and geometric, have proved critical in the achievement of these systems and with continued progress other practical devices are anticipated.

5. ACKNOWLEDGEMENTS

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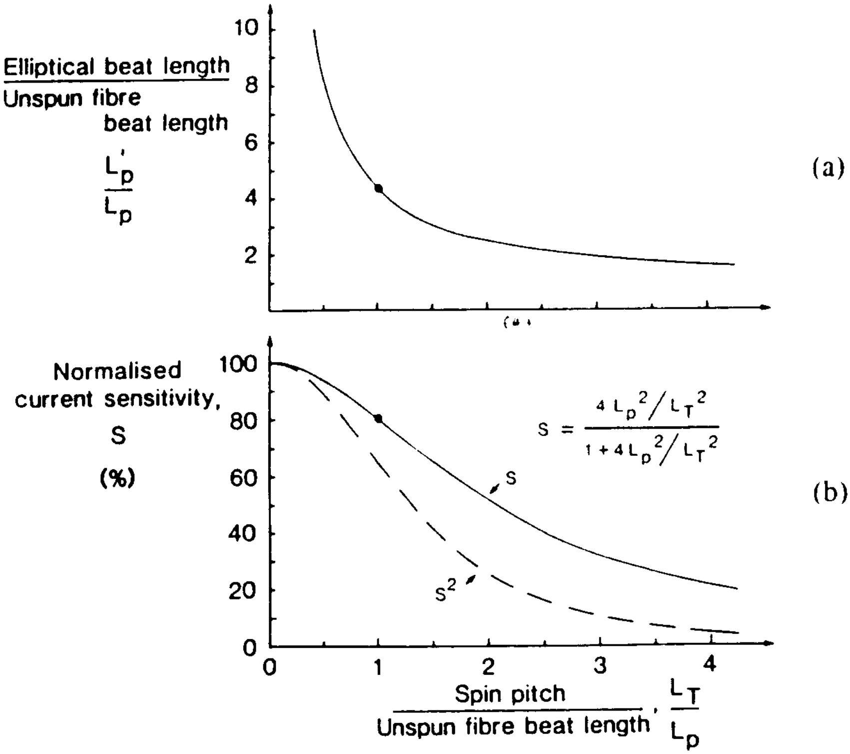

Fig. 1 a) Normalised elliptical beat length and b) relative current sensitivity as a function of the ratio of spin pitch to unspun fibre beat length.

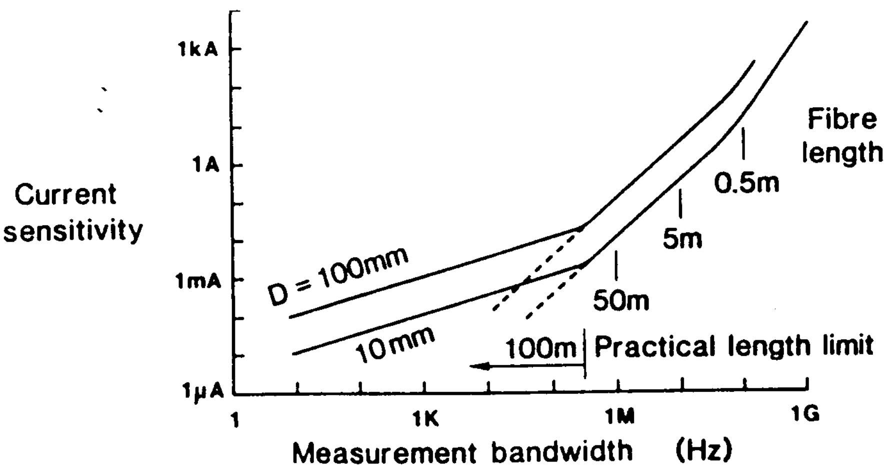

Fig. 2 Calculated current sensitivity of SEB fibre current sensors assuming the maximum fibre length permitted for a given bandwidth is used. The curve is shown for 10mm and 100mm fibre coils and is restricted to a practical fibre length of 100m.

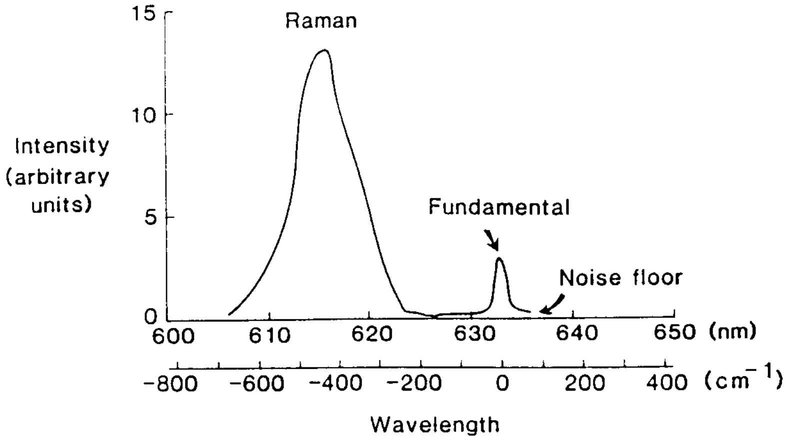

Fig. 3 Relative pump and signal levels after passing through 20m of Raman generating fibre and 7m of filter fibre showing pump rejection and Raman transmission.

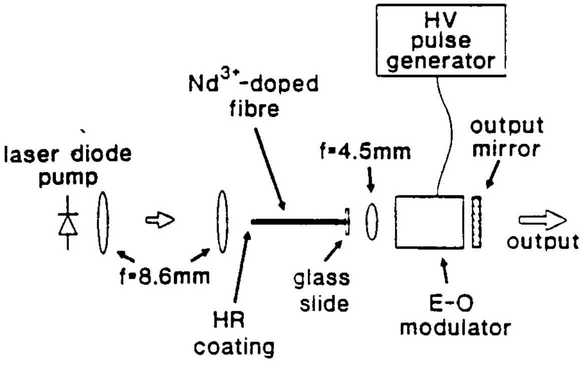

Fig. 4 Q-switch fibre laser configuration with integrated electro-optic Q-switching element. The glass slide reduces feedback into the amplifying fibre and prevents premature oscillation of the laser.

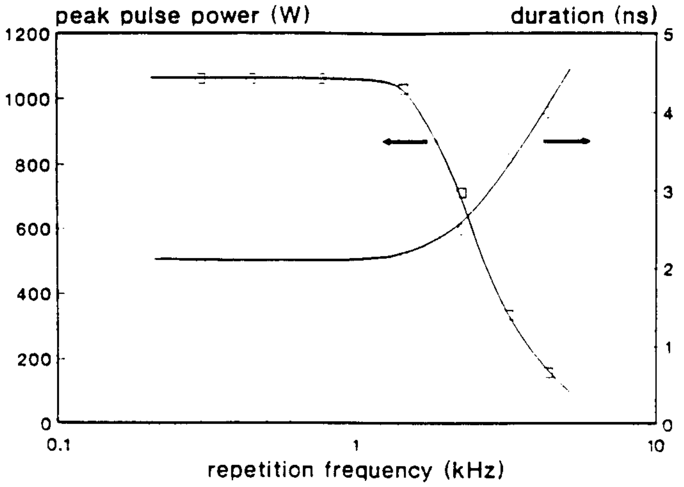

Fig. 5 Dependence of Q-switched pulse peak power and FWHM duration on repetition frequency for maximum pump diode output power of 89mW (22mW absorbed).

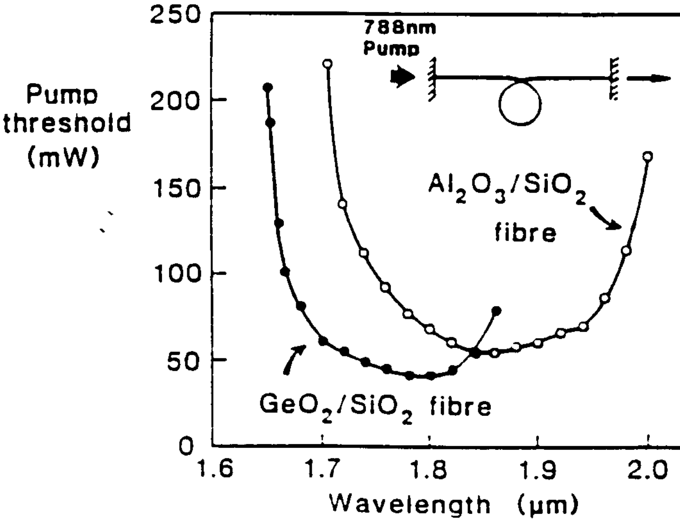

Fig. 6 Tuning curves for Tm^{3+} doped fibre lasers in GeO_2-SiO_2 or Al_2O_3-SiO_2 core fibres, with grating as output coupler.

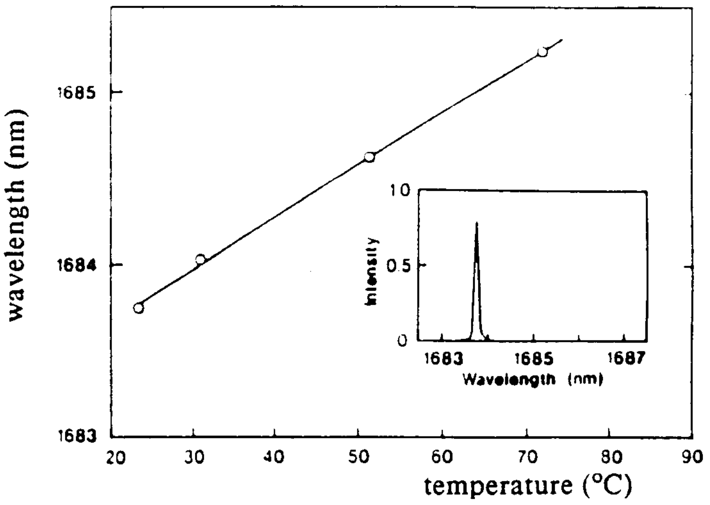

Fig. 7 Temperature tuning of Tm^{3+} doped GeO_2-SiO_2 core fibre achieved by Peltier heating a fibre Bragg grating integral in the laser cavity

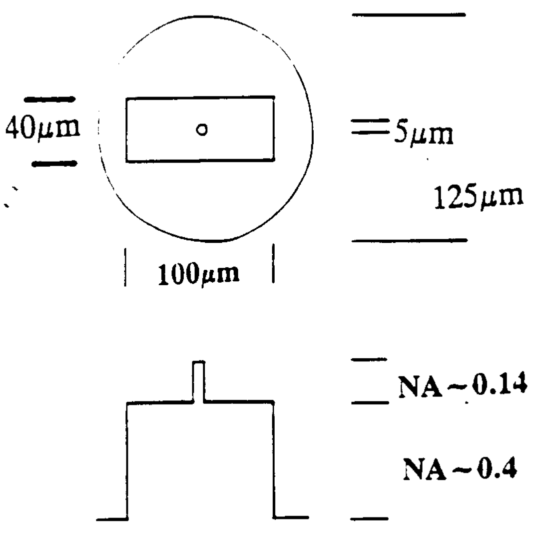

Fig. 8 Schematic showing the fibre geometry and refractive index profile for a typical cladding pumped fibre