Continuously distributed sensing via two photon excited fluorescence in doped optical fibre

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Abstract. The design and operating parameters of a new class of continuously distributed optical fibre sensor are described. Using counter-propagating pulses, two-photon excitation of fluorescence from ions doped into the fibre enables any position to be monitored. By this means temperature or strain may be sensed with high spatial and temporal resolution. As the doped fibre is transparent for single photon absorption at the wavelength of the light pulses, attenuation does not set an upper limit to its length.

1. Introduction
The upper state decay time ($\tau$) and the spectrum of the fluorescence emitted from optically active ions are dependent on the nature of the ions, the host in which they are embedded and the external environment; hence, temperature [1,2], strain [3] and fluid flow (via thermal conduction) [4] may be sensed. Laboratory resolutions of $< 1^\circ$C and strain sensitivities of c.250µε have been demonstrated with spatial and temporal resolutions limited by the size of the active sample and the decay time of the fluorescence respectively (a comprehensive survey of optical fibre sensors is given in [5]).

Fluorescence based sensors reported to date are effectively point sensors in which a small sample of active material is attached to the end of a conventional optical fibre. The optical fibre plays no part other than to transmit the excitation light to the sample and to return the resulting fluorescence to a remote detector. Quasi-distributed sensing of discrete locations using such single photon excited fluorescence is only achievable by connecting together multiple sensors. Likewise, sensors employing in-fibre Bragg gratings [6] are also “discrete” because they can only sense at those locations in a fibre where the gratings have been permanently written before installation. Other techniques such as spontaneous Raman scattering (SRS) and spontaneous and stimulated Brillouin scattering (SBS) [7,8] can achieve continuously distributed sensing but suffer from long acquisition times resulting from poor signal-to-noise ratios.

In this paper, truly continuously variable distributed sensing based on time correlated two photon excitation of fluorescence in doped fibres is described [9]. As fluorescence based sensing is equally applicable to mono- and multi-mode fibres, large diameter doped single crystal fibres may be used for environments currently inaccessible to glass fibres at temperatures in excess of 1500°C.

2. Principle of operation
Two photon excited fluorescence is generated in an ionic medium, such as a rare earth doped glass or crystal optical fibre, by the simultaneous absorption of pairs of photons without the involvement of an intermediate energy level. This process must be distinguished from the use of such media for “upconversion” purposes in which excitation of an intermediate level does occur [10]. The sum of the
photon energies in each pair must be at least as great as the energy gap from the ground state to the higher energy level from which the ions relax with emission of fluorescence photons. As the fluorescence’s properties do not depend on the route by which the ions have been excited, the use of a medium for sensing under two photon excitation is identical to when single photon excitation is employed.

Two photon excited fluorescence (TPF) may be exploited to achieve continuously distributed sensing by using counter-propagating light pulses to excite the dopant ions in the optical fibre. Since the generation of TPF requires the simultaneous absorption of pairs of photons, an enhanced fluorescence signal will be produced as the two pulses overlap – the TPF intensity is effectively proportional to the square of the total photon flux. The position of overlap can be scanned along the length of the fibre by introducing a variable time delay between the two pulses. The resulting fluorescence flash (usually in the visible region) from the overlap region is transmitted along the fibre and detected and analysed at one end. The temperature and/or strain to be measured are then derived from the sensor’s calibration. As the length of the sensed position depends only on the duration of the light pulses used (100ps is equivalent to c.20mm), there is also the potential for high spatial resolution. In this way, fracture locations in structures and localised temperature excursions in industrial plant can be identified. Also, the length of a fibre designed for two photon absorption is not limited by attenuation as the medium is transparent for single photon absorption.

The proposed sensor is illustrated in Figure 1. Oppositely travelling pulses meet in a loop of doped optical fibre and generate enhanced TPF at the point of overlap. The fluorescence then travels along the fibre and is detected at one end. Although a beamsplitter is shown in the schematic, an appropriate fibre coupler would be used in a practical sensor. Also, the use of a loop of fibre does not restrict the geometry of any proposed installation – the fibre is simply folded back along the original path. This also provides, if necessary, an additional means of separately calibrating the response to say temperature or strain if both are present; for example, in the outward direction the fibre can be rigidly fixed to the structure in question while in the return direction it is loosely attached.

![Figure 1](image)

Schematic diagram of the sensor. Counter-propagating laser pulses (A) and (B) in a loop of fibre meet at a location depending on their relative time delay.

### 3. Generation of TPF in the fibre

It may be shown [11] that pulses with identical durations and with a relative time delay $\Delta T$, energies $E'$ and $E$ respectively and photon energies $h\nu'$ and $h\nu$ respectively in a fibre of length $L$ and cross-sectional area of the core $A$, produce the following two photon excited fluorescence power at their overlap

$$P_{TPF}(t) = \frac{c\sigma N_0}{A} \frac{EE'}{(h\nu)(h\nu')} \exp\left(\frac{-t}{\tau_H}\right).$$

(1)
$N_1$ is the number density of the ground state ions, $\sigma$ is the cross-section for two photon absorption, $t = 0$ is the instant when the pump and probe pulses meet in the fibre, $h\nu$ is the energy of an emitted photon and $\tau_H$ is the decay time within the sensed overlap region. The temperature and/or strain dependent decay time ($\tau_H$) may be retrieved from the detected decay of the fluorescence intensity with time; in this example a single exponential has been assumed. Alternatively, the fluorescence spectrum can be time integrated and then analysed in various ways. For example in [12], the ratios of the fluorescence from thermally linked levels in both neodymium and ytterbium doped silica fibres were shown to be effectively insensitive to strain but strongly temperature dependent and thus capable of acting as a temperature calibration for a strain sensor based on decay time.

Typical ranges for the variable parameters in equation (1) are $\sigma = c.10^{-49}\text{ mm}^4\text{ s ions}^{-1}\text{ photons}^{-1}$, $N_1 = c.2\times10^{16}\text{ mm}^{-3}$ corresponding to a doping concentration of 1000ppm, $A = 4\mu\text{m}^2 - 1\text{mm}^2$, $L = m - kms$, $\tau_{ii} = ms - \mu$s, $E'/E = 1 - 10$, $\Delta t = c.100\text{ps}$ equivalent to a spatial resolution of $c.20\text{mm}$. The maximum pulse repetition rate is linked to the decay time as the fluorescence must have decayed after excitation before the next pair of pulses arrives. At room temperature, this corresponds to $1\text{ kHz} - 100\text{ kHz}$ depending on the specific combination of dopant and host. Note that the TPF power generated depends on the pulse energies and not their powers. Hence ultrashort pulses are not a requirement for two photon excitation of fluorescence and only has an impact on the spatial resolution in the fibre. By selecting longer pulses, the intensity can be maintained below that at which nonlinear effects such as self-phase modulation and continuum generation [13] and stimulated scattering [14] occur.

For pump and probe pulses with an average wavelength of say $1\mu\text{m}$, duration 100ps and peak power 10W, the number of TPF photons emitted in the flash at the overlap of a single pair of pulses in a fibre of core diameter $5\mu\text{m}$ is approximately $10^7$. This corresponds to the generation of $10^7 - 10^8$ TPF photons per second for pulse repetition rates of 1-100kHz. Even if only 1% of these photons is transmitted along the fibre and detected, this is sufficient to allow the fluorescence decay time to be measured rapidly with high precision. For a dopant with a short fluorescence decay time or as the fluorescence decay time is decreasing with increasing temperature, the pulse repetition frequency may be increased to offset any temperature dependent non-radiative decay mechanism present.

4. Optical fibre considerations

A distributed sensor based on TPF can use either single or multi-mode doped fibres. TPF is an incoherent process whose magnitude depends only on the photon flux assuming that the wavelengths involved satisfy the criterion for populating the upper state of the ion. In comparison, distributed sensing using in-fibre Bragg gratings or stimulated Brillouin scattering usually demand well defined wave vector directions as only found in single mode fibres. While the TPF signal is expected to be largest in a polarisation preserving single mode fibre of small cross-sectional area, the relaxation in favour of multi-mode propagation allows the technique to be extended to single crystal fibres such as sapphire with diameters of 100s microns. Although modal dispersion will reduce the spatial resolution, this is more than compensated for by their tolerance of much higher temperatures than glass fibres.

5. Optically active ion considerations

Most of the lanthanide or the transition-metal ions are candidates. From spectroscopic data, we have identified lanthanide ions such as praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), and ytterbium (Yb) as potential dopants for the optical fibre. Chromium (Cr) and titanium (Ti) are typical examples of transition–metal ions. They have been investigated in the search for new solid-state laser and upconversion media and, in the cases of praseodymium [15], neodymium [16], erbium [17], thulium [18] and ytterbium [19], have also been shown to be suitable for single photon excited fluorescence based sensing. Conveniently for this sensor, they possess absorption bands in the visible or near infra-red which can be excited by two photons from readily available lasers.
6. Laser considerations
Ultrasshort laser pulses of high peak power are not necessary for the operation of a TPF based sensor. As illustrated in the above numerical example, sufficient population of the dopant’s upper state is predicted to occur using pulses of energy 1nJ and duration 100ps (10W peak power). Such pulses provide a very high spatial resolution of c.20mm but are of low enough power to prevent the occurrence of competing nonlinear optical effects. Moreover, they are available from gain switched semiconductor diode lasers thus avoiding the complexity of a femtosecond laser system and may be mutually synchronised using an electronic variable delay.

7. Detection of TPF in the fibre
A TPF background may also be generated by the individual pulses but by judicious choice of different wavelengths and energies, this feature can be minimised or even eliminated entirely depending on the nature of the absorption spectrum. For example, if counter-propagating pulses of different wavelengths are used, they can be selected such that only one set produces background TPF. If these resonant pulses now have a lower flux than those of the other wavelength, the background will be suppressed relative to the TPF flash at the overlap by a factor equal to the ratio of the flux of the pulses. The TPF background can however also serve a very useful purpose as it can be treated as a calibration sweep of the fibre. An automated self-calibration can be performed many times per second enabling the sensor to respond in real time to a rapidly changing environment.

Figure 2 shows the results of a computational model based on equation (1) of the time development of the two photon excited fluorescence power. The normalised signal due to counter-propagating pulses overlapping at the mid-point of a fibre of length 50m is plotted against time. In this example, the time origin is at the instant of overlap, and the fluorescence decay time of the dopant is assumed to be 1ms, except for the position of overlap where it is 0.01ms due to local heating. The durations of the pulses are 100ps, the ratio of their photon fluxes is 10:1 and their wavelengths are such that only the less intense pulses cause TPF to occur on their own.

8. Conclusions
The design criteria for a fluorescence based optical fibre sensor, capable of continuously distributed sensing, have been presented. Two-photon excitation allows counter-propagating pulses to interrogate any ions at any position along the length of the fibre. Numerical modelling suggests that using relatively low power pulsed semiconductor diode lasers, a sufficiently large fluorescence signal is obtained to permit good temporal and spatial resolution.
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