Infra-red laser source using Tm:Ho optical fibre for potential sensor applications

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Abstract. In this work, a 1600nm Er fibre laser, which demonstrates a high pumping efficiency, has been used to pump an efficient all-fibre Tm:Ho laser system using a 0.3 m length of optical fibre. A low threshold of 33 mW and a slope efficiency of 0.6% have been achieved with operation at a wavelength of ~1870 nm. A cross-comparison has been made with the output of a device pumped by a 785 nm laser diode. The focus of the work is better and more compact sources for gas sensing in the near infra red region of the spectrum.

1. Introduction
Near infra red sources are particularly useful for gas sensing applications and this work explores the potential of solid state lasers, emitting light at wavelengths centred at ~2µm, to address such an important application. Tm:Ho co-doped fibres are usually chosen as the laser gain material for this spectral region as they can generate fluorescence centred at the above wavelength, when pumped by light from one of several commercially available laser diodes. A major advantage is their ‘eye-safe’ emission wavelengths, and thus they have been used for laser rangefinders, LIDAR devices, for remote sensing, in medical and dental applications and for cutting tissue and welding microscopic blood vessels. The emitting wavelengths are absorbed strongly by water, the main component of living cells and tissues.

A typical energy level diagram of both Tm³⁺ and Ho³⁺, doped into the silica used in optical fibre, is shown in Figure 1. The approach of co-doping Ho-doped silica with Tm³⁺ ions, to achieve lasing on the \(^5I_7\rightarrow 5I_8\) transition of Ho³⁺ [1][2], has opened up a range of possible pumping and energy transfer mechanisms through Tm³⁺ excitation. This includes the cw operation...
of a 1.064 µm pumped Tm-Ho-doped silica fibre laser [3], which has demonstrated a maximum output power of 11mW with a threshold pump power of 625 mW and at a slope efficiency of 1.8%. This relatively low efficiency is attributed to the presence of excited state absorption (ESA) from the \(^3\)H\(_4\) level, this having a more dominant influence on the kinetics of this energy level than does any other process. In comparison to pumping at 1.064µm, the inherent pump ESA of a 1212 nm Raman Fibre laser (RFL) is almost negligible [4] as it can excite the absorption peak of the Tm\(^{3+}\) ions from the ground \(^3\)H\(_6\) state to the excited \(^3\)H\(_5\) level, as shown in Figure 1. As a result, output powers of 400 mW at 1790 nm (with a slope efficiency of 23% and a threshold of 0.52 W) and 450mW at 1970 nm (with a slope efficiency of 31% and a threshold of 1.12 W) from RFL pumped Tm-Ho-codoped silica fibre laser have been achieved.

This work is designed to report work on the reduction of the threshold of the Tm-Ho co-doped fibre laser by using an efficient and low cost pumping scheme. The pump laser source considered is a 1600 nm Er doped fibre laser which is pumped by using light from a 980 nm laser diode. A fibre Bragg grating (FBG) pair with an optimum combination of reflectivities, together with a chosen length of high concentration Tm-Ho fibre, is configured to form an effective laser cavity.

2. Experimental setup and results

Figure 2 shows the configuration of an all fibre Tm:Ho fibre laser, pumped using an Er fibre laser, which is shown schematically in the dashed frame. The Er doped fibre laser is excited using light from a 500mW 980 nm laser diode and two matched FBGs with reflectivities of 98% and 30% are used as the wavelength selective mirrors of the laser cavity. The high concentration Er-doped fibre used in the experiment is custom-made and supplied by our research partner at Zhejiang University in China. Through a careful selection of the grating pairs used with different centre wavelengths, a range of Er doped fibre lasers could thus be generated.

The Tm:Ho doped silica fibre used in this work, supplied by the National Optics Institute in Canada, has a core diameter of 8.5µm and a numerical aperture (NA) of 0.21. The concentrations of Tm and Ho ions in the silica fibre used are 7900 ppm and 1300 ppm respectively. As the spectroscopic signal generated by the Tm:Ho fibre is beyond the measurement range of a conventional optical spectrum analyzer (OSA), a monochromator, type TMc300 (Bentham) is used in this work to cover the spectra range of the emission, using the PbS detector and operating with a spectral resolution of 1 nm. The grating pair forming the Tm:Ho laser cavity is centred at 1874 nm, with the reflectivity of around 60%, this being measured using the low spectral resolution monochromator.

2.1 Pump wavelength

Figure 3 shows the fluorescence spectra of a 0.8 m length of Tm:Ho fibre when pumped by light from three 26mW Er fibre lasers centred at wavelengths of 1557nm, 1580nm, 1600nm respectively. It is noticeable that the longer wavelength Er fibre laser has a higher pumping efficiency, although the Er fibre laser itself most commonly operates on the 1550 nm output band. The peak signals shown (centred at 1950nm in Figure 3) are the second order of the 975nm pumping.
2.2 Tm:Ho fibre - length effects
Fig 4 shows the fluorescence spectra from the Tm: Ho fibres of different lengths when pumped by using light from a 1600nm (26 mW) Er fibre laser. The results show that when the fibre length is 1 m, the fluorescence spectrum has two peaks, with one centred at ~1900nm (indicating the emission centre of the Tm$^{3+}$ ion spectrum) while the other, at ~1970nm, is contributed by the emission from the Ho$^{3+}$ ions. With the decrease of the fibre length, it is observed that the peaks of the fluorescence spectra shift to the shorter wavelength region, this being caused by energy transfer between the Tm$^{3+}$ and the Ho$^{3+}$ ions: the shift of the Tm$^{3+}$ spectra seen arises due to the re-absorption present. Thus in order to obtain a longer wavelength emission from the Tm: Ho fibre laser, it is essential to use a longer length of the fibre in the laser cavity. In this work, the length of the Tm:Ho fibre has been chosen to be 0.3m, taking into account both the emission peak and the intensity of the fluorescence generated.

2.3 Tm:Ho fibre laser output
Fig 5 shows the spectrum of the laser emission of a 0.3 m fibre when it is pumped using a 35mW 1600 nm Er fibre laser. Fig 6 shows the output power of the Tm:Ho fibre laser created, at a wavelength of 1.87 µm as a function of the 1600 nm Er fibre laser pump power.
**Fig. 4**  Fluorescence spectra of Tm:Ho fibre at different lengths when pumped by the same laser

**Fig. 5**  Tm: Ho fibre Laser spectrum (L=0.3m)
Through an optimization of the wavelength of the pump source and the length of the gain medium, the all-fibre Tm: Ho laser has demonstrated a much lower threshold (of ~33 mW), compared to the characteristics of lasers reported previously and as discussed in the Introduction. The slope efficiency, however, has shown to be low (0.6%) and this is mainly due to the low-reflectivity gratings being incorporated in the all-fibre laser cavities. However, with an increase of the cavity mirror reflectivity, the slope efficiency could be enhanced accordingly.

2.4 Cross-comparison with a laser diode pumped Tm:Ho fibre laser
To verify the optimization made with the Tm: Ho fibre laser configuration discussed above, the 1600 nm Er doped fibre laser shown in Figure 1 is replaced by a 50 mW 785 nm laser diode whereas for the Tm:Ho laser cavity, the same arrangement is kept. The results obtained from both pump sources are cross-compared and shown in Figure 7, where a much lower laser threshold, when pumped a 1600nm source, has been demonstrated.

3. Discussion
It has been observed from the experiments carried out that the pump efficiency of the Tm: Ho laser is determined not just by the pump power but also is dependent on the emission wavelength of the pump laser. In this work, a 1600nm Er fibre laser has been specifically chosen as the pump source and achieved practically through careful design of the Er laser cavity created using both an appropriate length of the Er fibre and the central wavelength of the grating pair.

In addition to the above, the main characteristics of the Tm: Ho fluorescence spectrum, i.e. the fluorescence peak wavelength and intensity are also determined by the length of the Tm: Ho fibre enclosed within the laser cavity. In this work, a 0.3 m Tm: Ho fibre has been chosen as the laser medium as its fluorescence emission, when pumped by a 26 mW 1600 nm Er fibre laser, allows optimum operation at a wavelength of 1870 nm.
In summary, this work has proposed a practical, innovative all-fibre laser configuration developed through an optimization of both the pump Er fibre laser and of the Tm: Ho fibre laser itself and as a result, a significant improvement on the laser threshold has been achieved, compared to what has been reported in literature and with the same Tm:Ho laser cavity when pumped by a 785 nm laser diode. As a consequence, there is a relaxed demand on the initial pumping power required for the laser diodes used, simplifying the configuration and reducing the cost of a laser which is important for practical applications, such as near infrared gas sensing. Work is continuing to explore these applications.

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