Compact Tm-doped fibre laser pumped by a 1600 nm Er-doped fibre laser designed for environmental gas sensing

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A B S T R A C T

In this work, the compact all-fibre linear Erbium (Er)-doped fibre lasers, operating at wavelengths of 1584 nm and 1600 nm have been described and optimized, with an aim to achieve better pumping conditions for a Thulium (Tm)-doped fibre laser. Optimization of the system has been carried out involving the studies on the different lengths of the Er-doped fibre and the different grating pairs used to achieve 173.5 mW of laser power at 1600 nm under bidirectional pumping at 980 nm. The designed Er-doped fibre laser at 1600 nm has been utilized successfully to pump longer wavelength Tm-doped fibre laser. The obtained laser power (output of Tm-doped fibre laser) of 35.5 mW at 1874 nm and 10.6 mW at 1995 nm is effective for environmental gas sensing, as these wavelengths align well with the absorption spectra of greenhouse gases such as CO_2. The laser offers high power (tens of milliWatts), good directionality and a compact overall packaging with the diode pumping, making them ideally suited to 'in-the-field' use.

1. Introduction

1.1. Environmental monitoring at longer wavelengths

In order to monitor pollutant gases using optical methods of sensing and measurement, wavelengths in the region of ~2 μm typically show greater sensitivity over that at shorter wavelengths. Key examples are seen in CO_2 gas detection, given the severe impact on global warming from the continuously increased concentration of this 'greenhouse' gas in the atmosphere (further details are discussed in the literature and the work of Bogue [1] provides an excellent overview and technology roadmap of the need for novel gas sensors in the petrochemical, gas and water industries). As can be seen in Fig. 1, the absorption cross-section of CO_2 is much higher in the longer wavelength region (around 2 μm) than that in the region around 1.5 μm [2]. The database was also tabulated in [3]. In addition, tuning to an absorption line with a narrow line laser yields strong absorption, enhancing the sensitivity to the detection of CO_2. Therefore, lasers operating in the wavelength range from 1800 nm to 2000 nm, with features of the compact design and easy 'in-the-field' use, are particularly important for sensing the important environmentally impacting gases. Thus a sensor system based on a compact, lightweight, and all-fibre configuration, enables itself to be easily used outside the laboratory and has considerable potential for sensing a wide range of pollutant gases [4].

In our previous work, the test of sensing CO_2 gas had been done, which showed the good property in the application of the gas sensing [3,5]. The as-designed Tm-doped fibre laser based gas detection system has shown itself to be successful in offering a stable means of detection of CO_2, and be superior in terms of the selection of the operating wavelength. Thus its optical spectrum is fitted to a specific absorption line of the gas showing a stronger absorption cross section, in a particular longer wavelength absorption band. The results were comparable with the spectral features available from the HITRAN database.

In this work, such a Tm-doped fibre laser has been discussed as a gas sensing device which shows considerable promise, due to its longer wavelength operation at considerable power levels. In the previous work reported in other literature, Tm-doped fibre lasers with the very high output powers have been realized, but the configurations are often in somewhat complex, such as double cladding [6,7], large diameter fibre core [7] (both of which make the fibre expensive), or cladding pumping [8], and additionally the

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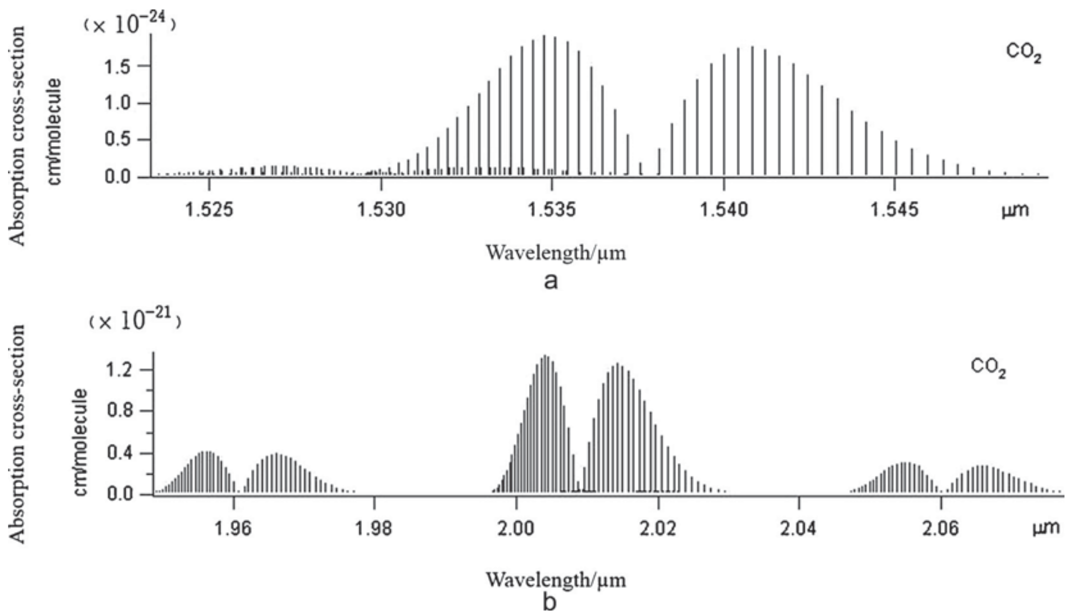

Fig. 1. The absorption spectra of the CO_2 gas in the wavelength of (a) 1.5 μm and (b) 2 μm.

high pump powers [9] are also required. The Tm-doped fibre laser reported in this work is able to provide a simple, compact, inexpensive system, which is easier to set up and use, and is ideal for a wide range of applications of environmental gas sensing.

1.2. A foundation on prior work for the target of this research

This paper reports on the use of the advantageous spectral characteristics of the Tm [10,11], which forms the active dopant of the fibre. For the targeted wavelength range of the emission spectrum, the absorption should be located at around 1.6 μm (the $^3F_4 \rightarrow {}^3H_6$ transition is highly efficient) in silica fibre [12]. In previous work, the influence of the host material composition on the emission efficiency has been discussed [13]. The specification of the Tm-doped fibre to be optimized for laser action [14] is important, hence, the Tm-doped fibre used in this work was a home-made fibre to allow for optimization, rather than the commercial fibre.

Building on prior research dating from 1993 [15] and 1994 [16] by Yamamoto et al. and beyond, the optimization of an Er-doped fibre pump laser was investigated as the basis of an effective Tm-doped fibre laser system. Er-doped fibre lasers and travelling-wave amplifiers operating in the region of ~1.5 μm were first demonstrated in 1986 [17] and 1987 [18], since then they have attracted considerable attention from research groups across the world. Such a laser can very effectively act as an inexpensive pump source for a compact all-fibre linear configuration laser, operating in the wavelength range of ~2 μm, by taking advantage of the wide fluorescence spectrum in the targeted wavelength range.

The target of this work is to build an optimized, simple, compact environmental gas monitoring laser system: employing the Er-doped fibre laser (at wavelengths of around 1.6 μm) to pump a Tm-doped fibre laser in the wavelength range of around 2 μm, to form a compact all-fibre linear configuration. The Tm-doped optical fibre used in this work was specifically designed and fabricated by the Central Glass and Ceramic Research Institute (CGCRI) in India, in order to optimize the fibre absorption efficiency, at around 1.6 μm, and the emission efficiency, at around 2 μm to achieve high output powers for the sensor application. Thus the research investigates the design and configuration of the Er-doped fibre laser to obtain an optimal pump output power, followed by a description of the longer wavelength Tm-doped fibre laser pumped by former to create a compact, stable and high efficient laser operating at 2 μm region for environmental sensing.

2. Configuration of the Er-doped fibre laser pump

A schematic of the laser system is shown in Fig. 2, where an output power of the Er-doped fibre laser of 173.5 mW was achieved. The Er-doped fibre laser comprised a 2.0 m length of Er30 fibre as a gain medium, Fibre Bragg Grating (FBG) pair with reflectivities of 99.4% and 22.1% (written in fibre type PS1250/1500, a photosensitive single mode fibre provided by Fibercore, of fibre diameter 125 μm, mode field diameter of 10.4 μm, numerical aperture 0.12, and cut-off wavelength of 1123 nm) and bidirectional pumping at 980 nm.

2.1. Optimization of the Er-doped fibre

In this study, for simplicity, a commercial 980 nm Laser Diode (LD) was employed as the source to pump the Er-doped fibre. Therefore, the critical issue is the optimization of the gain media and the reflector elements, that is, special attention has been paid on the choice of Er-doped fibre, and as a consequence of that choice, the grating pairs are discussed below. To optimize the performance of the Er-doped pump laser, three different types of Er-doped fibre were considered as the gain medium to optimize the output power of it, as shown in Table 1.

In order to evaluate the performance of the Er-doped pump laser with the above fibre types, initially a series of different lengths of the same type of Er-doped fibre are compared to obtain the optimal length of fibre for use in this system. Following that, the features of three different types of Er-doped fibre with the optimized lengths are compared, with a view to specifying an optimized Er-doped fibre configuration as the gain medium for the longer wavelength fibre pump laser. Based on the experimental setup shown above, pump powers available from the LD of 13.9 mW, 24.7 mW and 10.2 mW were launched into Er30, Er110 and Er40 fibres with different lengths respectively. These power levels used were exactly right for the generation of effective gain in the medium. An analysis of the outputs from these devices shows that the optimized lengths for each of the different types of Er-doped fibre are approximately 2.0 m, 0.5 m and 1.0 m for the Er30, Er110, Er40 fibres, respectively.

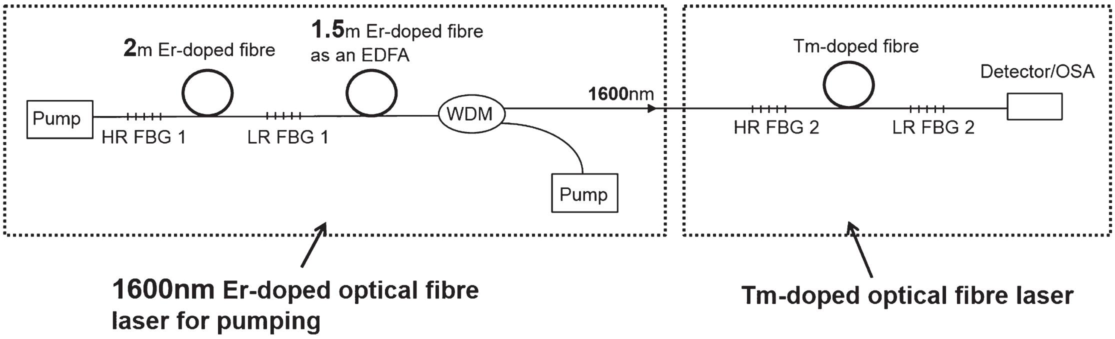

Fig. 2. Experimental set-up of the Tm-doped optical fibre laser system. The Er-doped fibre laser is used as the pump source. Pump: 980 nm laser diode with the maximum output power of 500 mW; HR FBG: High reflectivity FBG; LR FBG: Low reflectivity FBG; 1 and 2 indicate 1600 nm and 1874 nm/1995 nm gratings respectively; Detector: output power monitor; OSA: Optical Spectrum Analyzer. WDM: Wavelength Division Multiplexer.

Table 1
Details of three types of Er-doped fibre.

	Core diameter	Cladding diameter	Absorption	Numerical aperture	Cut-off wavelength
Er30	4 μm	125 ± 2 μm	30 ± 3 dBm	0.2 ± 0.02	800–980 nm
Er110	4 μm	125 ± 2 μm	110 ± 10 dBm	0.2	800–980 nm
Er40	4 μm	125 μm	Not available	Not available	Not available

A cross-comparison of the emission efficiency of each of these three optimized lengths can be seen from Fig. 3, where the emission efficiency of 2.0 m long Er30 both at 1584 nm and 1600 nm are the highest. Thus 2.0 m long Er30 was chosen as the optimized gain medium.

2.2. Optimization of the laser grating pairs

Apart from the optimization of the gain medium, the optimization of the grating pairs is also very important. Two key aspects, the operational wavelength and the actual grating reflectivities, have been taken into consideration. The Bragg wavelengths of the two gratings should be closely matched during the grating writing process. The reflectivity of the highly reflective grating is required to be as high as possible and also to be matched with that of the lower reflective grating, to yield the optimal performance, as summarized in Table 2.

A number of (sixteen) grating pairs were evaluated and selected from the gratings at 1584 nm. The prime aim was to fabricate a selection of reflectivities in the range from approximately 18% to 43%. Thus the grating pairs can be separated into three groups according to their reflectivities, as shown in Table 2. The low

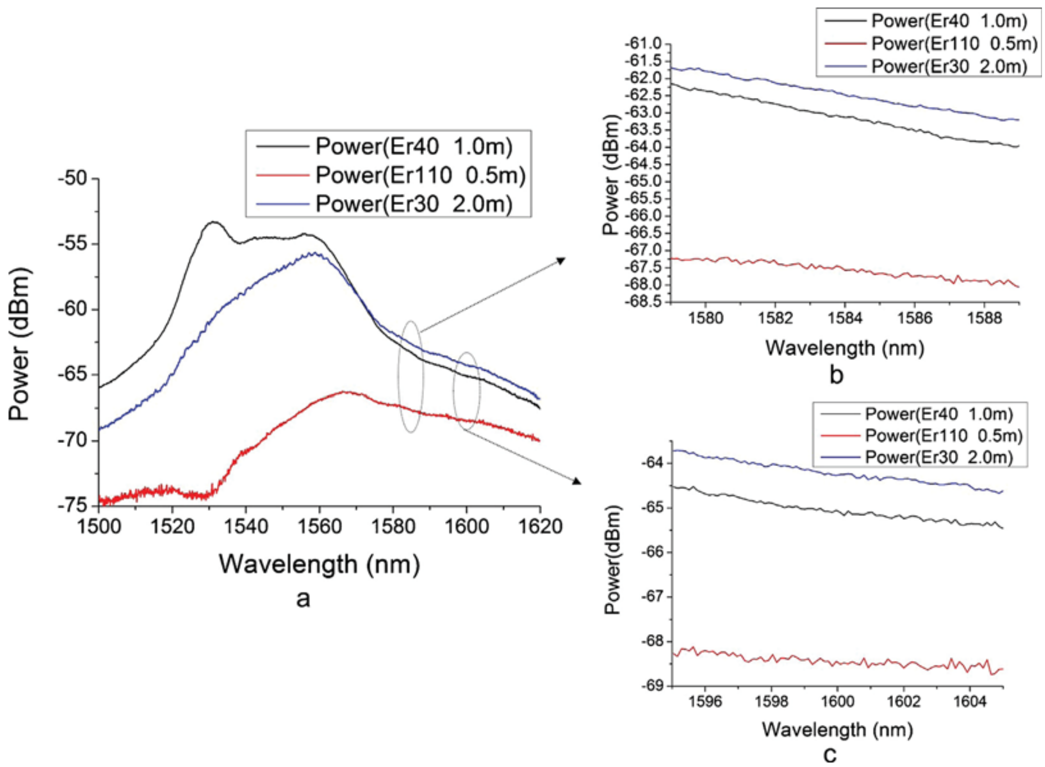

Fig. 3. Fluorescence spectral comparison of three different types of Er-doped fibres, each one with an optimal length (pump power 10.2 mW). (a) over the wavelength range from 1500 nm to 1620 nm; (b) at a wavelength of around 1584 nm; (c) at a wavelength of around 1600 nm.

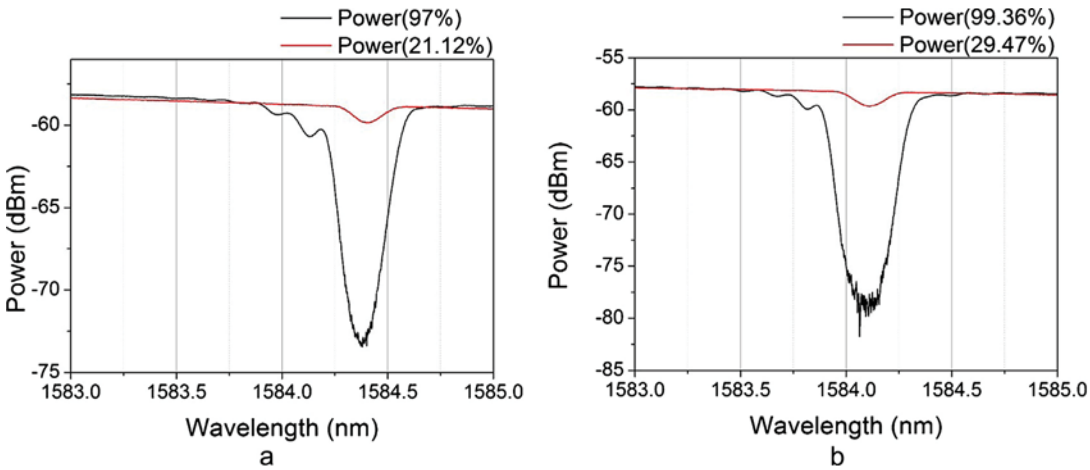

Fig. 4. Spectra of two typical grating pairs used.

Table 2
Matched grating pairs at a wavelength of 1584 nm used in this work.

	HR1: 97.0%	HR2: 97.5%	HR3: 99.4%
LR matched with HR	21.1%	18.4%	21.9%
	21.4%	23.8%	23.9%
	23.0%	29.8%	29.5%
	24.3%	41.3%	
	25.6%	42.6%	
	26.7%		
	34.1%		
	36.6%		

reflectivity gratings in the range from ~18% to ~43% were investigated to optimize the performance of the grating pairs used. Fig. 4 shows the spectra of two typical grating pairs with high and low reflectivities of 97.0% and 21.1%, 99.4% and 29.5%, respectively.

Each grating pair was used to form the cavity to create a laser system pumped initially by one 980 nm LD using three types of Er-doped fibres with optimized lengths. The results obtained were noted and cross-compared, showing that the output power is always the highest (among the use of the three optimized length fibres) when a 2.0 m long Er30 fibre is employed in the system. As a consequence, 2.0 m long Er30 fibre represents the optimized gain medium. Fig. 5 demonstrates this point, where an optimized grating pair comprising the 97.5% and the 18.4% reflectivities was selected from several grating configurations. An evaluation of the situation has shown that the preferred condition is that the reflectivity of the HR grating is as high as possible, with a lower reflectivity for the LR grating, in order to yield the highest output power from the laser system.

2.3. Optimization of the Er-doped fibre laser pump at 1584 nm and 1600 nm

As illustrated in Fig. 2, the Er-doped fibre laser is connected to a length of fibre between the LR grating and the WDM, which is used as an Erbium doped fibre amplifier (EDFA) to improve the overall output power of the system. Through evaluating the performance of Er-doped fibres with different lengths, it was found that 1.5 m Er30 fibre is optimal. Thus a bidirectional pump Er-doped fibre laser system operating at 1584 nm, consisting of two 980 nm LDs, 2.0 m and 1.5 m long Er30 fibres, and grating pair with HR of 97.5% and LR 18.4%, was created, resulting in an output power in total of 130 mW. Using the same approach, another Er-doped fibre laser operating at a wavelength of 1600 nm and using the same configuration was created, and in this case an output power of up to 173.5 mW was observed. The grating pair used comprised an HR of 99.4% and a LR of 22.1%. Fig. 6 illustrates the output power of this configuration of Er-doped fibre laser as a function of pump power, and Fig. 7 shows the emission spectra of Er-doped fibre laser operating at 1600 nm.

3. Tm-doped fibre laser operating at wavelengths of 1874 nm and 1995 nm

The optimized Er-doped fibre laser at 1600 nm with output power of 173.5 mW was used to pump the Tm-doped optical fibre laser as shown in Fig. 2. In this case, by changing the grating wavelengths to 1874 nm and 1995 nm respectively and adjusting the fibre lengths, the output power of the Tm-doped fibre laser could be varied. A series of tests were carried out through examining the known fluorescence characteristics of the Tm ion to obtain the optimized result. In addition, a monochromator with a relatively low resolution was utilized to observe the fluorescence spectrum (the OSA previously used did not operate in the 2 micron wavelength range).

Although a wide range of commercial Tm-doped fibres are available, in our research we found that they are not the optimum choice for this sensing application, as the considerably high pump power from the LD source is desired to pump them. As a result, a Tm-doped active fibre was specifically designed and fabricated at CGCRI, India. Here the alumino-silicate and the alumino-germano-silicate with suitable amount of Al were used as host materials for Tm^{3+}, and the amount of Tm ions was controlled carefully, because too high Tm^{3+} concentration in the single mode fibre configuration can weaken the laser performance due to the clustering of rare-earth icons in the alumino-silicate glass host. In some cases, $Yb(Ytterbium)^{3+}$ and Tm^{3+}, in a proportion of approximately 1:1, were co-doped in the glass host, which enhances the laser performance at the wavelength of ~2 μm because of the energy transfer of $Yb^{3+} \rightarrow Tm^{3+}$ [10,14].

The Tm-doped optical fibres (type NM210, with Tm-ion concentration ~4000 ppm, and the absorption spectrum are plotted in Fig. 8) with different lengths, were used in this work to investigate the relationship with the threshold pump power. Fig. 9 shows the results indicating that the optimized lengths are 7.0 cm and 10.0 cm for lasing wavelengths of 1874 nm (b) and 1995 nm (c), respectively.

Three grating pairs, at a wavelength of ~1874 nm are considered and optimized, as shown in Table 3. Fig. 10 shows the wavelength matching of these grating pairs, as seen, there are several troughs around the target wavelength arising from water absorption (and not the gratings themselves).

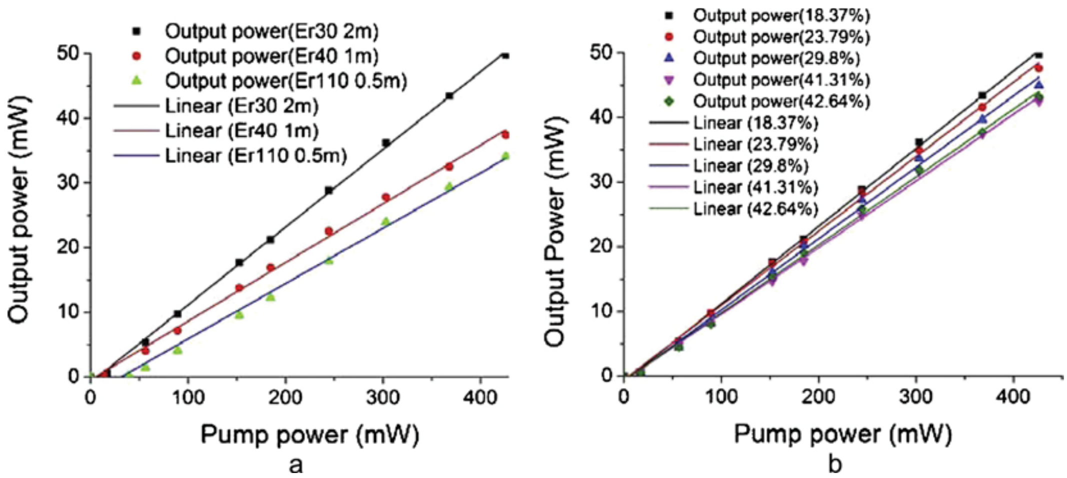

Fig. 5. Output power as a function of pump power. (a) Cross-comparison of three types of Er-doped fibre lasers using a fixed grating pair, HR 97.5% and LR 18.4%; (b) 2 m Er30 fibre laser using HR grating 97.5% and various LR gratings with different reflectivities.

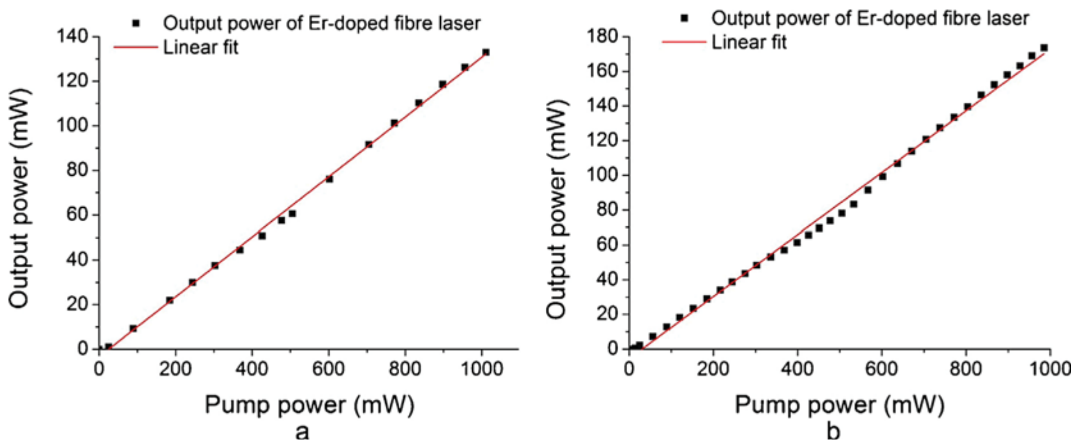

Fig. 6. Output power of the Er-doped fibre laser as a function of pump power. (a) The Er-doped fibre laser operating at a wavelength of 1584 nm; (b) the Er-doped fibre laser operating at a wavelength of 1600 nm.

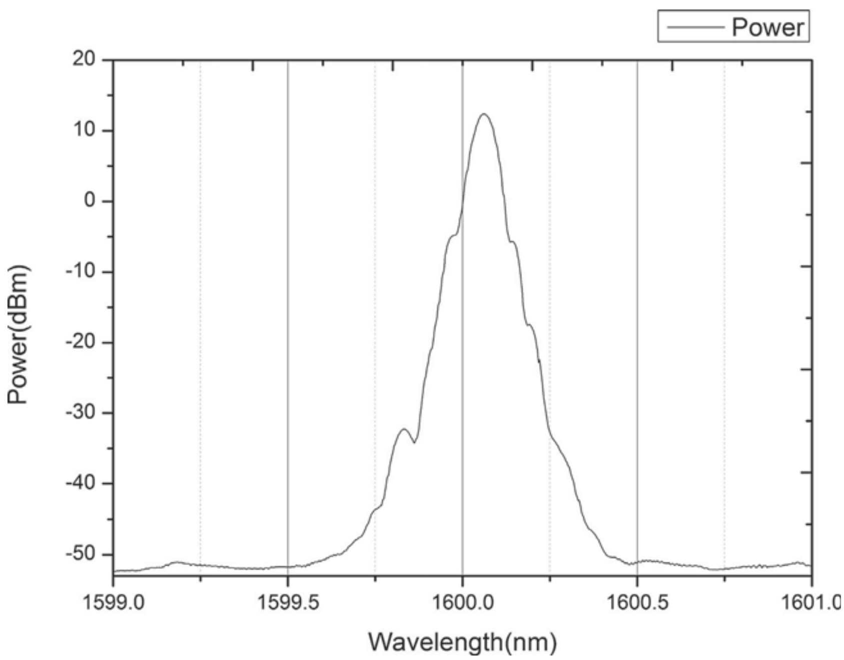

Fig. 7. Emission spectra of Er-doped fibre laser operating at 1600 nm.

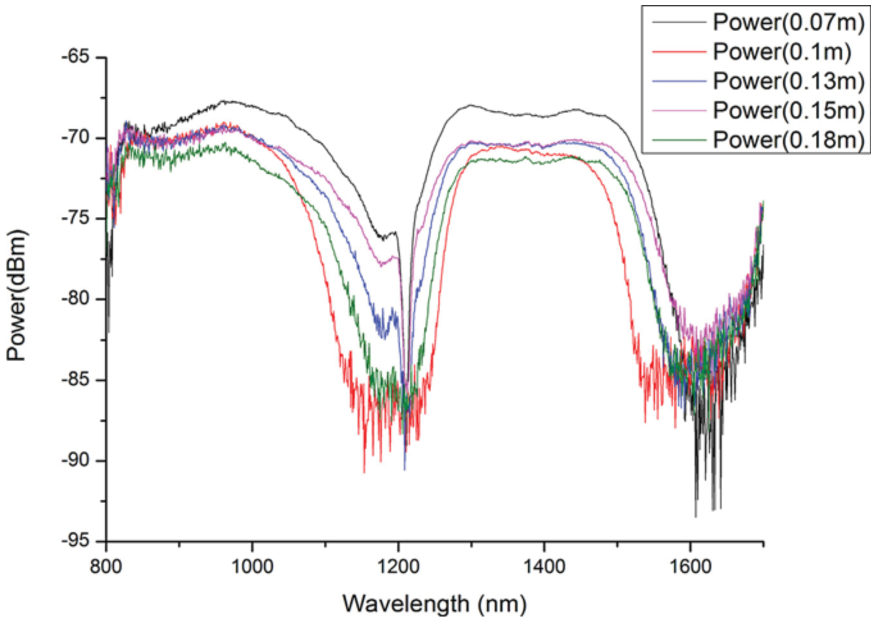

Fig. 8. The absorption spectrum of NM210 type Thulium doped fibre which is cut into different lengths to illustrate the absorption property.

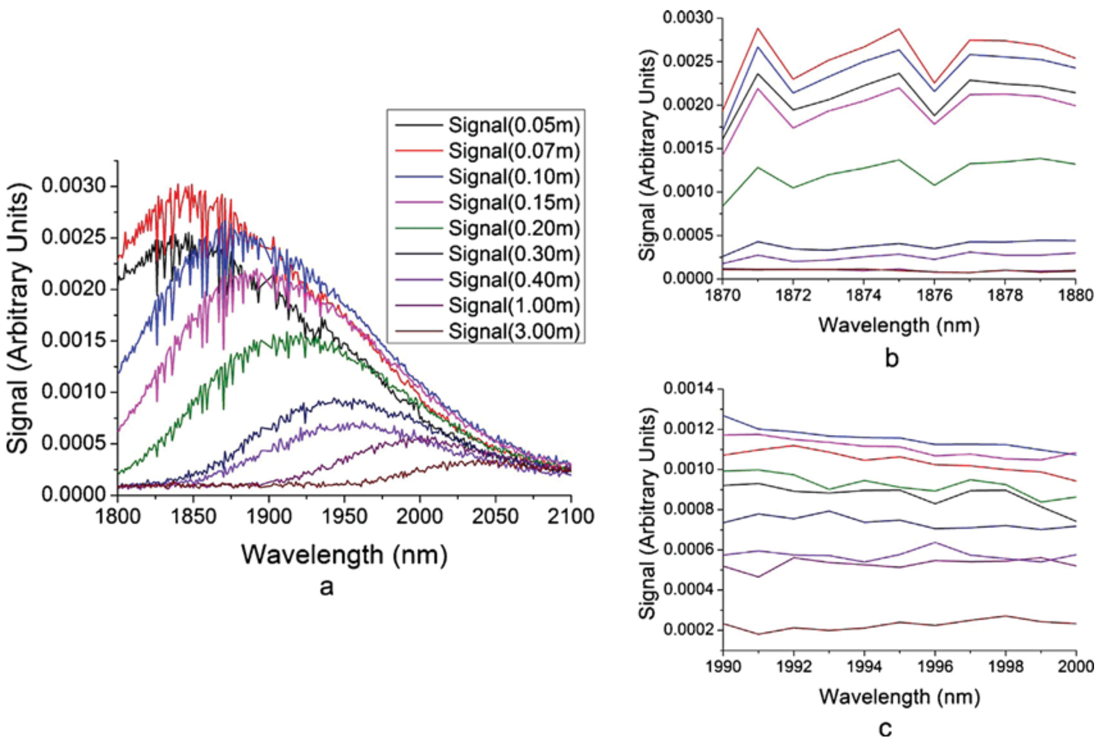

Fig. 9. Fluorescence spectrum of Tm-doped fibre of different lengths pumped by the 1600 nm Er-doped fibre laser with the power of 60 mW. (a) wavelength from 1800 nm to 2100 nm; (b) wavelength of ~1874 nm; (c) wavelength of ~1995 nm. The colour lines in image (b) and (c) are uniform with them in image (a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In order to optimize the Tm-doped fibre laser, the three grating pairs indicated above were used with a 7.0 cm long Tm-doped fibre to create a set of fibre lasers. The output power from these lasers was detected using a power metre and the data was recorded.

Table 3
Matched grating pairs at a wavelength of ~1874 nm.

	HR1 No.1: 99%	HR2 No.8: 99.56%
LR matched with HR	No.3: 70.0% No.5: 82.0%	No.5: 82.0%

Fig. 11 illustrates that the grating pair, comprising gratings No.1 and No.3, provides the optimum configuration. When pumped by the Er-doped fibre laser with the maximum output power (130 mW at 1584 nm), the Tm-doped fibre laser (with the optimized grating pair and a 7.0 cm long Tm-doped fibre) emitted the output power of up to 9.75 mW at 1874 nm.

Further, a set of gratings were fabricated and different samples of Tm-doped fibres were selected to obtain a series of optimal grating pairs coupled to the different gain media respectively. Several grating pairs, with LR reflectivities from ~90% down to ~40% were evaluated, and according to the results obtained, the LR

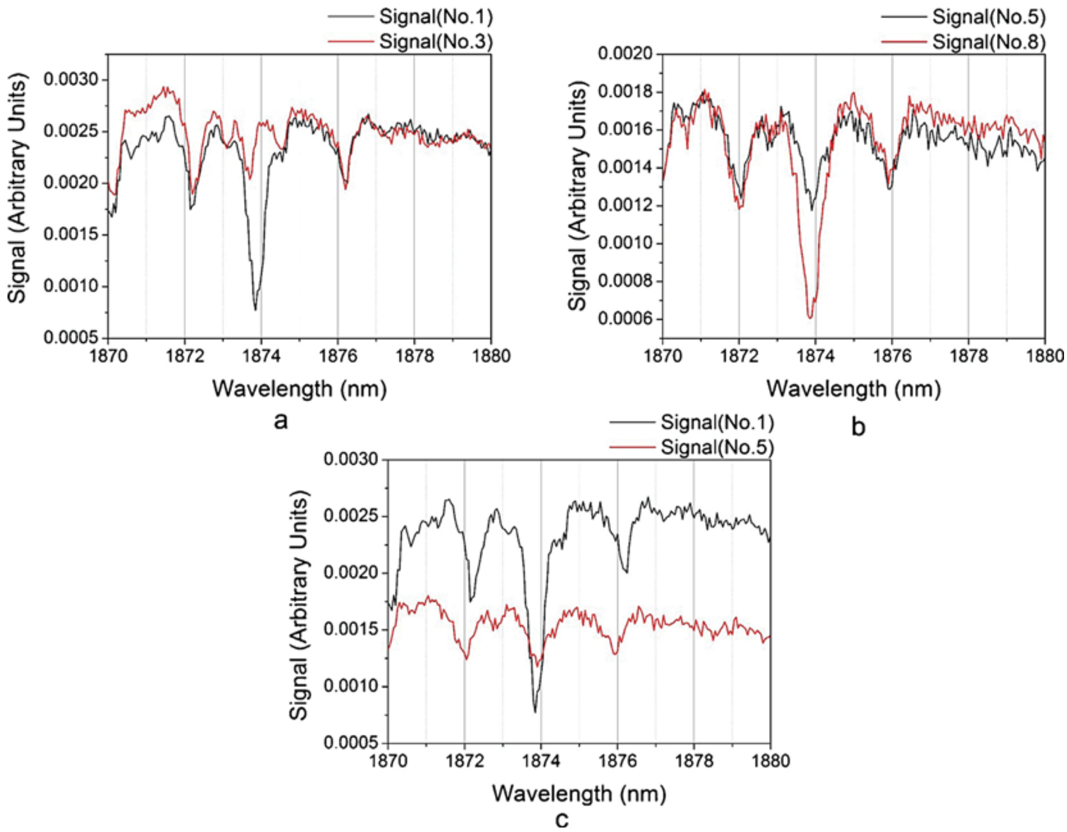

Fig. 10. Spectra of matched grating pairs at a wavelength of ∼1874 nm. (a) No.1(99.0%) and No.3(70.0%); (b) No.8(99.6%) and No.5(82.0%); (c) No.1(99.0%) and No.5(82.0%).

reflectivities of ∼50% and ∼75–80% at wavelengths of 1874 nm and 1995 nm respectively, were determined as the optimal reflectivities. With regard to the use of Tm-doped fibre, it was found that the highest output was achieved from a 25 cm-long NM150 fibre (of Tm concentration ∼1000 ppm). Subsequently, optimized grating pairs at a wavelength of 1874 nm (with HR 99.9% and LR 50.3%) were evaluated, and a maximum output power of 35.5 mW was obtained when the combined laser cavity was

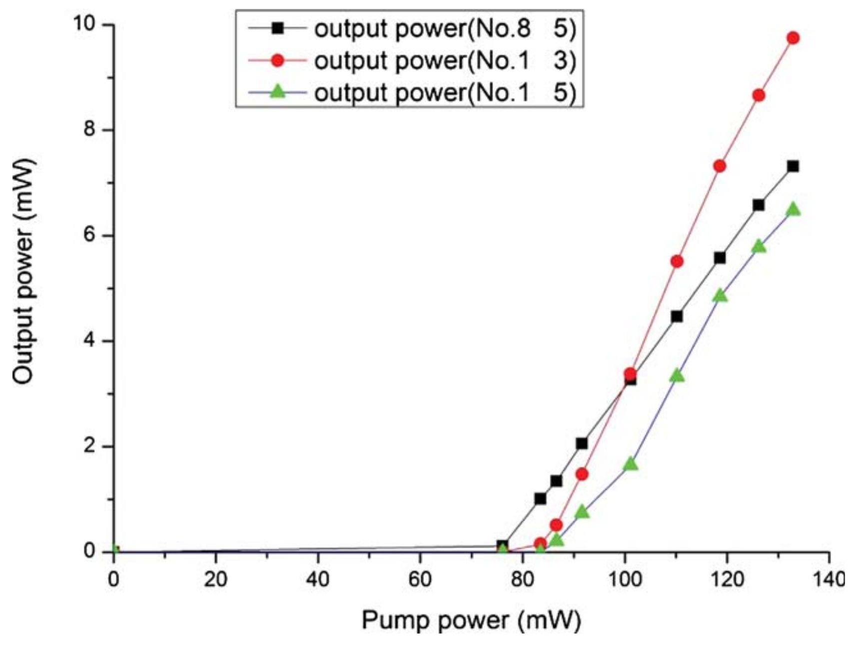

Fig. 11. Output power as a function of pump power. The inset shows the performance of the different Tm-doped fibre lasers with three different grating pairs as reflectors, indicated by the different colour lines. The black colour indicates grating pair of No.8(99.6%) and No.5(82.0%) as reflectors; The red colour indicates grating pair of No.1(99.0%) and No.3(70.0%) as reflectors; The green colour indicates grating pair of No.1(99.0%) and No.5(82.0%) as reflectors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

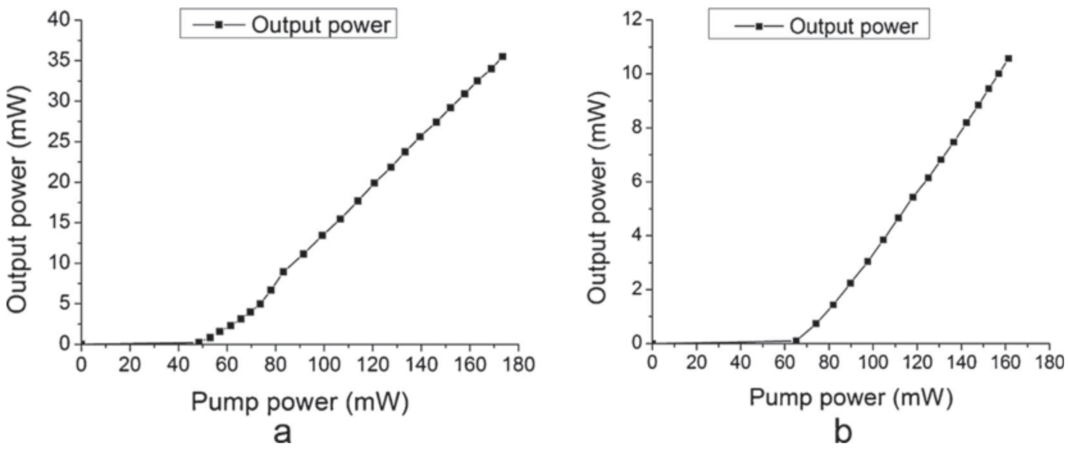

Fig. 12. Output power data from the Tm-fibre laser as a function of pump power in 1874 nm (a) and 1995 nm (b).

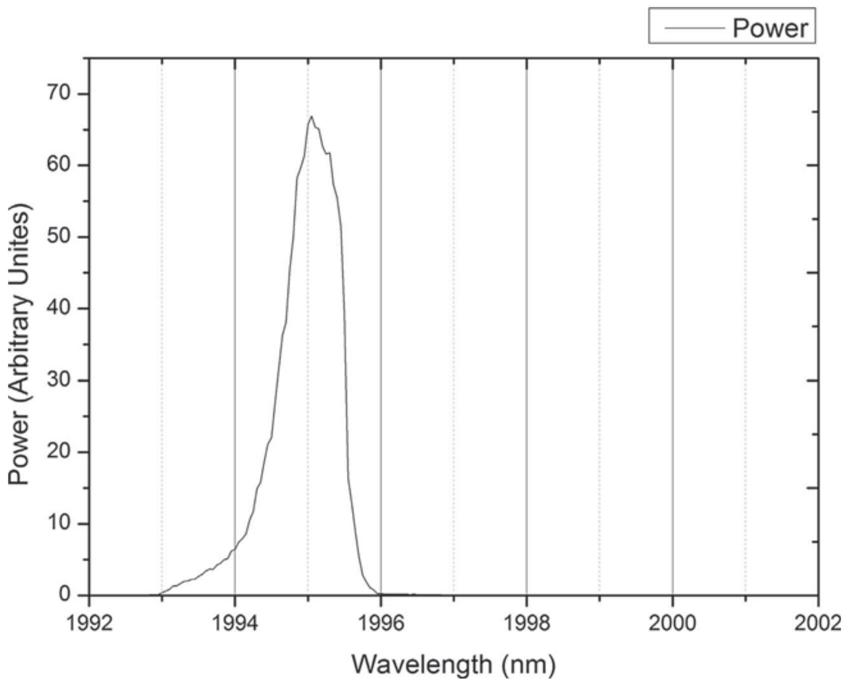

Fig. 13. Emission spectra of Tm-doped fibre laser operating at 1995 nm.

pumped by an Er-doped fibre laser (with maximum output power of 173.5 mW at 1600 nm). This Er-doped fibre laser was then used to pump a Tm-doped fibre laser consisting of a 25 cm-long NM150 fibre enclosed by a grating pair (HR 99.5% and LR 79.6%) at a wavelength of 1995 nm, yielding a peak output power of 10.6 mW, as can be seen from Fig. 12. In addition, the emission spectra of Tm-doped fibre laser operating at 1995 nm is shown in Fig. 13.

Table 4
Tabulated use of optical gas sensing techniques for a range of gases for use in the gas supply, water and wastewater and petrochemical industries (from Bogue et al. [1]).

Industry	Application	Typical gases sensed
Gas supply	Leak detection(field)	CH_4
	Processing/distribution	CH_4, water vapour, H_2S, odours
	Safety(plant)	CH_4
Water/wastewater	Safety	CH_4, other combustibles
	Health	CO, O_2 deficiency, Cl_2, O_3, CO_2, H_2S
	Other uses	H_2S/odours, CH_4(in CHP systems)
Petrochemicals	Safety	CH_4, HC_S, H_2, other combustibles
	Health	CO, CO_2, HF, H_2S, VOC_S, BTEX, HCN, propylene oxide, O_2 deficiency etc.
	Process monitoring and control	O_2, H_2, CO, H_2S, COS, NH_3, arsine, water vapour, ethane, ethylene etc.
	Environment	NO_X, SO_2, CO, CO_2, NH_3, etc.

4. Suitability for environmental sensing and discussion

The work presents an optimized, especially grating reflectivities and gain media, diode pumped Er-doped fibre laser at 1600 nm with output power of 173.5 mW, in order to pump a Tm-doped fibre laser to achieve significant power in the spectral region of ~2 μm for environmental monitoring applications, especially for the CO_2 sensing. Utilizing the designed Er-doped fibre laser operating at wavelengths of 1584 nm and 1600 nm as a pump source, a Tm-doped fibre laser at 1874 nm and 1995 nm has been developed with lasing output power of 35.5 mW and 10.6 mW, respectively. The absorption efficiency of CO_2 gas in the region of ~2 μm is much higher than that in the shorter wavelength regions, therefore, the powers available are sufficient for the CO_2 sensing. In addition, the configuration of this all-fibre linear fibre laser created in this work is simple, compact and well suited to the environmental gas sensing applications in the field.

Table 4 (from the work of Bogue et al. [1]) summarizes the potential of the compact gas sensors for a number of industrially-relevant areas, which indicates that such compact and even portable gas sensors are in high demand. Therefore, the gas sensing system based on all-fibre linear fibre laser reported in this work with many desired properties is the ideal candidate for making such portable gas sensing instruments, which is lightweight and largely immune to vibration-effects with being battery driven. Studies of the performance of this gas sensing system discussed herein in monitoring a range of environmental gases will be the subject of future reports.

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