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F.Z. QAMAR[1,2]✉
T.A. KING[1]

Self pulsations and self Q-switching in Ho^{3+}, Pr^{3+}:ZBLAN fibre lasers at 2.87 μm

[1] Department of Physics, Damascus University, Khald Ben Alwaleed St., Alfarouk, Damascus, Syria
[2] Laser Photonics Research Group, School of Physics and Astronomy, the University of Manchester, Manchester M13 9PL, UK

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ABSTRACT The temporal characteristics of the output of a single-clad Ho^{3+}, Pr^{3+}-co-doped ZBLAN fibre laser pumped by a Nd:YAG laser at 1064 nm has been found to exhibit a range of cw, self pulsation and self Q-switching output dynamics, dependent on the excitation and fibre conditions. An interpretation is considered based on stimulated Brillouin scattering and the effect of the excited state absorption (ESA). For long fibre ($\sim$ 13 m) and for uni-directional pumping, the output was a continuous wave (cw), but for bi-directional pumping, a significant decrease in the stability of the output is observed and the output displayed well developed self pulsations. A train of self Q-switched pulses with mean pulse duration of 767 ns, a peak pulse power of about 2.8 W and an average power of 183 mW and with more than 80% pulse-to-pulse stability has been observed when pumped with 4.4 W into each end of the fibre. Self pulsation phenomena are also observed in unidirectional pumping for shorter fibre lengths of $\sim$ 9.2 m at high pump power and for 1.5 m fibre length at all pumps power.

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1 Introduction

Self-pulsing behaviour in fibre lasers has been variously reported in several fibres emitting in the range between 1–2 μm. The causes of this behaviour have been explained in several ways as due to the presence of ion-pairs or clusters in heavily doped fibre lasers [1] or stimulated Brillouin or Raman scattering effects in bi-directional propagation (i.e. standing wave lasers) high-loss fibre laser cavities [2, 3].

The role ion-pairs (or ion clusters) are most commonly invoked as the theoretical explanation of the performance of heavily-doped erbium-fibre amplifiers and self-pulsing instability observed in erbium-doped fibre lasers (EDFL's) at $\lambda = 1.55$ μm and thulium doped fibre lasers at $\lambda \approx 2$ μm [1, 4–8]. It was demonstrated in an Er fibre [9] that for low ion-pair concentrations the EDFL operates continuously, where the proportion of ion pairs in the doped fibre $x \leq 5\%$, but for high ion-pair concentrations $x \geq 5\%$ the laser was self-pulsing. The ion clusters were identified as playing the role of a saturable absorber, where one ion of two neighbouring ions each in the $^4I_{13/2}$ state of Er^{3+} transfers its energy to the other, producing one up-converted $^4I_{9/2}$ ion and one ground-state ion. The time associated with this process is sub-microseconds, and the up-converted ion quickly decays to the $^4I_{13/2}$ state, resulting in the loss of one excited erbium ion. This process, acting as a quenching effect, requires high ion pair concentrations to take place, and thus produce an efficient saturable absorption effect which leads to self pulsing behaviour [10]. A theoretical model of a three-level system with ion clusters as saturable absorbers has been studied in [11]. On the other hand, a new theoretical model has been considered where the mechanism of self-pulsing or self Q-switching is the result of power-dependent thermo-induced lensing in the erbium fibre that originates from the excited-state absorption at the laser wavelength [12]. A train of self Q-switched pulses of 3.3 μs duration and at 13 kHz repetition has been obtained from an Er-doped fibre laser ring that has an erbium-doped fibre cooled to 4.2 K to enhance the saturable absorption effect inside the fibre [13].

The self pulsing in a dual-wavelength erbium-doped fibre laser operating simultaneously at 1.536 and 1.548 μm has also been reported [14]. The interval between the two wavelengths of $\sim$ 12 nm could be varied by using a Bragg grating. The results have been theoretically interpreted using the ion-pair model.

Similar behaviour has been found experientially in Tm fibre lasers operating efficiently from $\sim$ 1.9 to $\sim$ 2.0 μm on the $^3F_4 \rightarrow {}^3H_6$ quasi-three-level transition [8]. It was established that the $({}^3F_4, {}^3F_4) \rightarrow ({}^3H_6, {}^3H_4)$ upconversion ion-pair process is significant in heavily Tm^{3+}-doped silica fibres. This process causes the saturable absorption that is indicated by the presence of relaxation oscillations. A detailed theoretical model that describes the ion-pair dynamics relevant to the Tm^{3+}-doped silica system has been presented [8]. It has been found that for large emission-to-absorption cross-section ratios of Tm^{3+} ions doped into silica and for pump rates for which stable output is predicted, the oscillations are weakly damped before the steady state is reached [15]. The experimental results show that for low pump powers, the output is characterised by a train of self pulsing output and at certain higher powers the self pulsing converts to self Q-switching with a train of multi-pulses, whereas further increase in the input pump power results in quasi-cw operation of the laser [8].

✉ Fax: +963-112129825, E-mail: kamar@scs-net.org

Pulsed characteristics of a cw diode pumped neodymium doped double-clad fibre laser have been described [16]. It was verified that the multi-longitudinal mode laser started oscillating in a pulsed manner. Maximising the emission rate by increasing the pump power, the lasing system favoured pulsed emission over cw emission. Simultaneous oscillation of a large number of modes in homogeneously broadened lasers may lead to spontaneous mode-locking of modes over a certain frequency range regardless of the number of modes contained in that range. Adding extra modulation by the use of a semiconductor saturable absorber mirror (SESAM), self pulsing was changed into self mode-locked emission. The conditions to achieve this type of output were inferred from the self pulsing state [16]. Recently, the self pulsation of a Nd^{3+}-doped fluoride fibre laser was experimentally demonstrated using a Tm^{3+}-doped fluoride fibre pumped at 808 nm as a saturable absorber. The self-pulsation was stable for a certain pump power range, achieving a pulse with duration and peak power of $\sim 4.5\ \mu s$ and ~ 1.5 mW at 230 mW pump power [17].

Self pulsing and self Q-switching effects have also been observed in ytterbium fibre lasers [2, 3, 18, 19]. Stimulated Brillouin scattering has been considered as the theoretical explanation for self pulsation phenomena in these fibres [2]. Self Q-switched pulses with peak power of 10 kW and few ns duration have been generated from a diode pump ytterbium-doped fibre laser exploiting distributed back-scattering in the fibre as a passive Q-switching mechanism [18]. Back-scattering in a fibre is associated with stimulated Rayleigh and Brillouin scattering and can be enhanced with the use of a long single mode optical fibre or a fibre Bragg grating in the laser cavity. The laser generates a supercontinuum, a high-brightness white light spectrum covering the complete window of transparency of the silica fibre in the IR region [18]. Stable self Q-switched pulses with a duration of about 2 ns at 29.4 MHz have been obtained from a double-clad Yb^{3+}-doped fibre laser by exploiting SBS fibre nonlinearity and enhancing it by adding single mode fibre optics. The SBS provides strong feedback in the laser cavity in the form of short SBS relaxation oscillation pulses which are equivalent to an increase in the Q-factor by a few orders of magnitude during a short period of time. Thus, the pulse duration depends on the dynamics of SBS rather than the cavity lifetime. The pulse duration is also independent of doped ion concentration; it is only determined by the interaction period between the transverse acoustic wave and the core [19]. Self Q-switching based on back scattered SBS has been also reported for a Er-doped fibre laser producing 2.2 ns pulses [20]. Additionally theoretical modelling of the dynamics of a self Q-switched fibre laser with a Rayleigh-stimulated Brillouin scattering ring mirror has also been reported [21].

In this paper, the temporal behaviour of a 4-level single-clad Ho^{3+}, Pr^{3+}co-doped ZBLAN fibre laser emitting near 3 μm is reported. To the best of the author's knowledge this is the first time the dynamics have been studied both for the mentioned fibre and for fibres emitting at near 3 μm in general. For a long fibre the output is found to be steady cw while the output becomes pulsed for shorter fibre. Also for the first time, bi-directional pumping for the fibre is demonstrated to be an effective method to break the stability of the steady cw in linear fibre cavities with a long fibre and creates regular self Q-switched pulse train. A stable self Q-switched pulse with duration of 767 ns and 2.8 W peak power has been obtained from a fibre length of 13 m at a total pump power of 4.4 W into both ends of the fibre.

2 Experimental arrangement

The standard single-clad fluoride fibre (Fibrelabs, Japan) in this study had concentrations of 30 000 ppm molar Ho^{3+} and 3000 ppm molar Pr^{3+}, a core diameter of 15 μm, a numerical aperture of 0.13, an intrinsic loss of ~ 30 dB/km at 800 nm and supported single mode operation. The fibre was double end pumped by a 10 W single mode vertically polarised Nd:YAG laser operating at 1064 nm. The experimental setup is shown in Fig. 1. The laser beam passed through a half wave plate ($\lambda/2$) and then split by a polarizer into two beams. The arrangement gave the advantages of controlling the pump power, with no need to change the current that supplied the lamp of the pump laser and thus maintaining the beam profile of the laser for all output powers and, using the same laser to pump both ends of the fibre, avoided any problems arising from the use of different sources to simultaneously pump the same fibre. The first pump beam is focused by an objective lens with NA = 0.25 and then reflected from a 45° dichroic mirror to launch into the first end of the fibre. The 45° dichroic mirror was $\sim 99\%$ high reflectance (HR) at the pump wavelength and $\sim 97\%$ high transmission (HT) using an antireflection coating at the lasing wavelength. The mirror allowed the separation of the 2.87 μm output from the pump power. The second beam was focused by a NA = 0.25 objective lens into the second facet of the fibre. The end was butted with a mirror, HR at the lasing wavelength and HT at the pumping wavelength. The cavity was then formed by a $\sim 4\%$ Fresnel reflection surfaces and a high reflectance mirror, en-

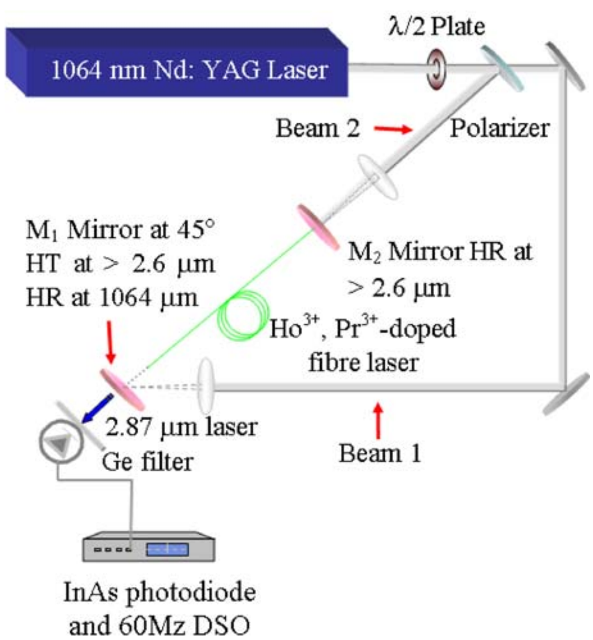

FIGURE 1 Experimental set up for bi-directional pumping of Ho, Pr-doped fibre laser

abling pumping of both ends of the fibre at the same time. The temporal profile of the laser output was measured using an unamplified, liquid nitrogen cooled InAs photodiode (Judson J12D) with a response time of approximately 2 ns, connected to a 60 MHz digital storage oscilloscope (Tektronix TDS210). A thin polished Ge filter was utilized to ensure that the detector only measured the lasing wavelength.

3 Laser dynamics

A maximum pump power of 9 W was available, a fibre length of ∼ 13 m was used and the launch efficiency was greater than 80% respect to the incident power, thus, the total launched power into the fibre after taking in account the transmission of the objective lens and the reflectance of the 45° mirror, was ∼ 6.3 W. This generated a maximum average laser output power of 250 mW at 2.87 μm. The temporal profile of the output showed that the output tended to be cw for all pump powers when there was no feedback or no pumping into the second end of the fibre. Figure 2a and b show the temporal profile of the laser output when the fibre was pumped at only one end. In Fig. 2a, the polarizer was adjusted to give maximum transmission, (i.e. maximum power in beam one, see Fig. 1) which was then launched into the fibre while the second beam was blocked. In contrast, Fig. 2b shows the temporal behaviour with opposite direction pumping, i.e beam one is blocked and beam two is active with the reflected beam from the polarizer maximized and launched into the fibre. When bi-directional pumping was applied to the fibre, the stability of the output of the fibre reduced so that the stable cw output changed into unstable self-pulsation output. This instability originated from increasing the feedback scattering and it will be discussed in the following section. The self-pulsation

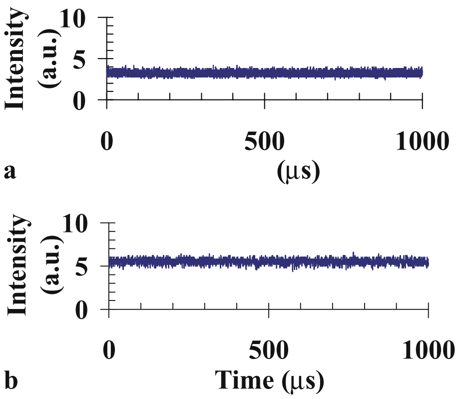

FIGURE 2 cw output for uni-directional pumping of the 13 m fibre laser by 9 W launched into one end: (**a**) Output through 45 deg mirror M_1, (**b**) Output through M_2

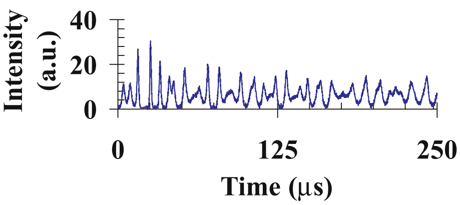

FIGURE 3 Fibre laser output through M_1 with 2 W pump launched into one end of the 13 m fibre and 6 W into the other end

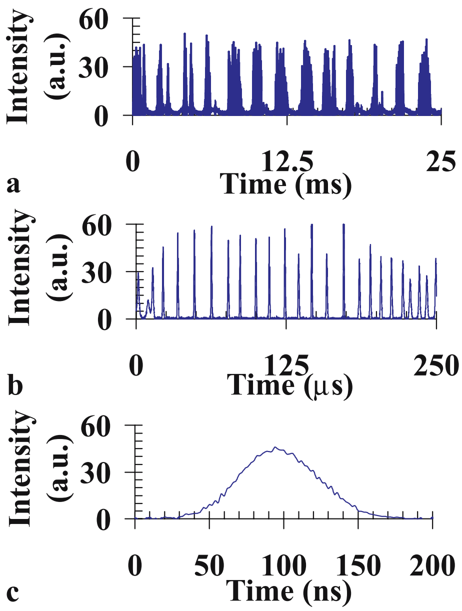

FIGURE 4 Chaotic bursting pulses train and individual pulse when 3.5 W launched into one end of the 13 m fibre and 5.3 W pumped into another end

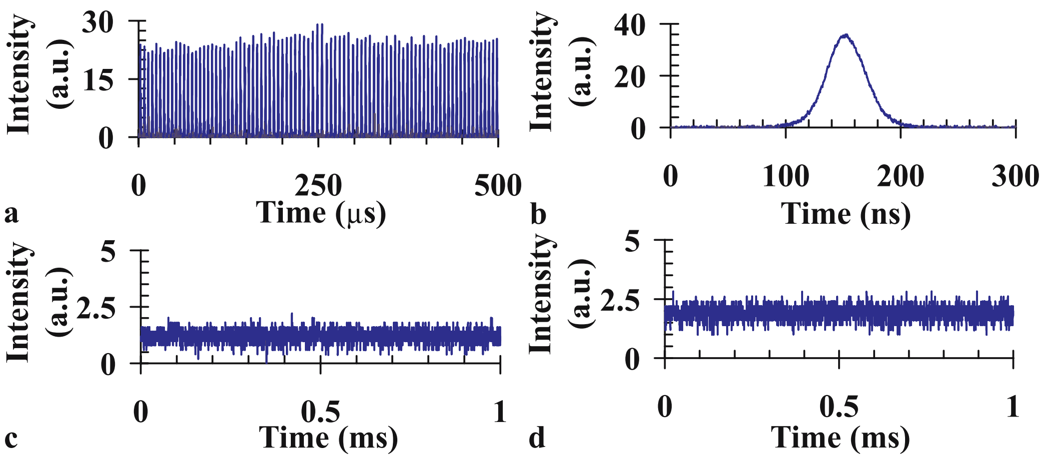

FIGURE 5 (**a**) A train of regular self-Q-switched pulses at 85 kHz repetition rate, and (**b**) an individual pulse with a duration of 767 ns, when equal pump power of 4.5 W launched into both ends of the 13 m fibre. (**c**) and (**d**) cw output from M_1 and M_2 when one of the pumped beams is blocked and the fibre is unidirectionally pumped

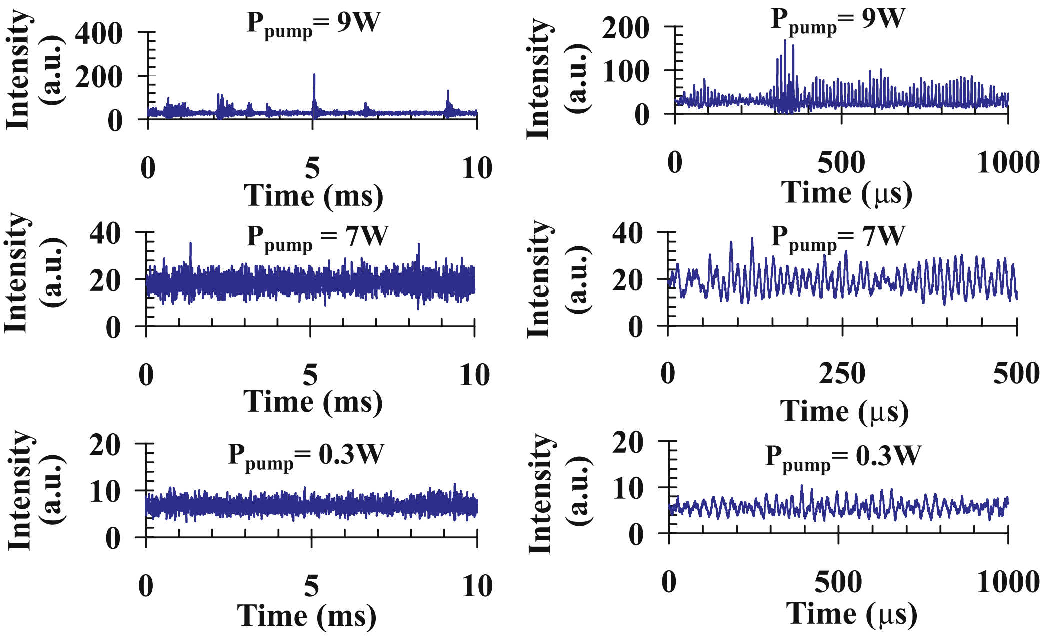

FIGURE 6 Dynamical behaviour for the output of the 9.25 m fibre laser when pumped by 9, 7 and 0.3 W launched from the single transverse mode laser. The dynamics cover the range between random bursts of pulses to quasi-cw lasing

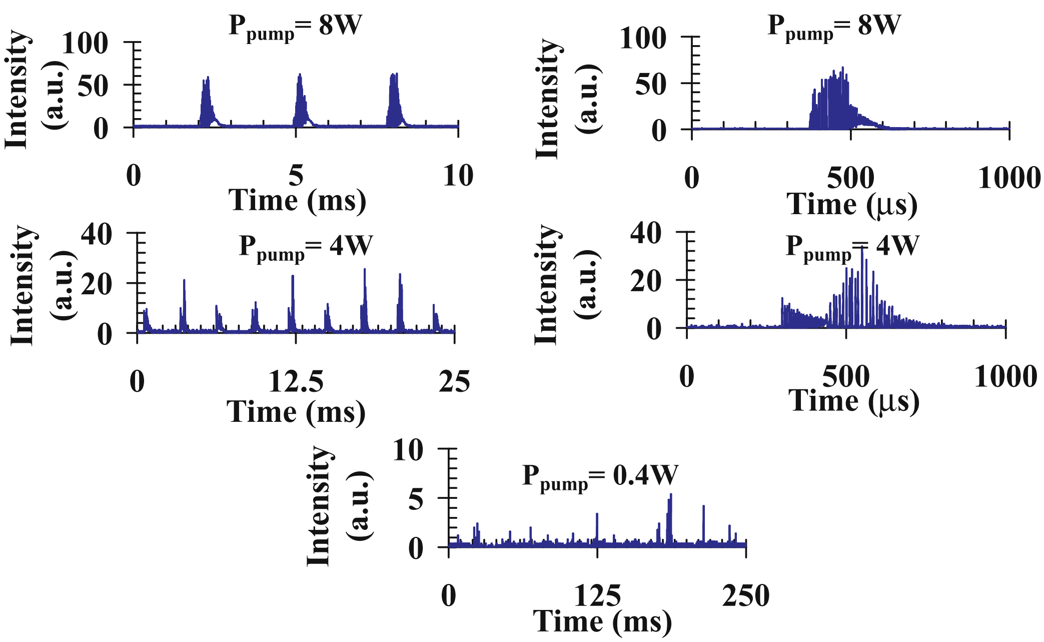

FIGURE 7 Chaotic dynamic behaviour of the 1.5 m fibre pumped by 8, 4 and 0.4 W launched from the single transverse mode laser

was characterised by a quasi-cw output when there was a large difference in pump powers into the two ends; further reduction of this difference led to a self pulsing output with 100% modulation depth and to complete self Q-switching when the pump power into both ends, was nearly equal. Figure 3 shows quasi-cw output with pumping of 7 W into one end and 2 W into the other end. Increasing the pump power pumped into the M_2 direction will reduce the pump power pumped into the M_1 direction after the polarizer results in self-pulsations, as is seen in Fig. 4 where one end of the fibre was pumped with 3.5 W and the other end with 5.5 W. A train of high intensity pulses (Fig. 4a), with average power of 183 mW and pulse duration 633 ns (Fig. 4c), at ∼ 85 kHz repetition rate (Fig. 4b), has been obtained. The bursts of high intensity pulses become a regular self Q-switched pulse train with more than 80% pulse-to-pulse stability, when the fibre was pumped by equal powers of about 4.5 W. Figure 5a and b shows a train of self Q-switched pulses and an individual pulse for an output with an average power of 183 mW, pulse duration of 767 ns, and a peak power of ∼ 2.8 W at ∼ 85 kHz repetition rate. However, the fibre operated in the cw regime with an average power of 70 mW, when one of the pumped beams was blocked, as shown in Figs. 5c and d.

The temporal behaviour of the fibre was seen to be affected by the length of the fibre. For instance when a shorter fibre (∼ 9.25 m), the optimum length for cw operation, was used in a second experiment, the temporal profile showed that the fibre operated cw for pump powers up to 7 W. However, a further increase in pump power resulted in creating relaxation oscillation pulses followed by cw operation, Fig. 6.

The temporal profile for very short fibre (∼ 1.5 m) confirmed that the fibre, and at all input pump powers, always operated in a self pulsing regime, where the output consisted of a burst of relaxation oscillation pulses, as illustrated in Fig. 7. Bi-directional pumping for the previous two lengths of 9.25 m and 1.5 m showed very weak influence on the temporal behaviour of the output.

4 Discussion and the mechanism of self pulsation

Generally, using single mode cw lasers to pump fibres that support single transverse mode propagation induces a dynamical behaviour dependent on the fundamental nonlinear interactions between the pump and the fibre. The primary nonlinear mechanism is stimulated Brillouin scattering (SBS). Various studies on SBS in optical fibres have demonstrated that under a single transverse mode cw pumping into a single mode fibre, remarkable chaotic dynamics with modulation depth ∼ 100% can be generated for all conditions of operation, starting from the SBS threshold and with no evidence of stable state operation [22].

A theoretical explanation based on coupled pump and Stokes nonlinear fields and material equations, has established that the role of nonlinear reflection and its interplay with nonlinear gain in the SBS interaction is responsible for the dynamical behaviour [23]. Further studies on SBS, taking into account the external feedback reflection from both ends (∼ 4% Fresnel reflection) of the fibre have also been reported [24]. It has been found that at lower pump intensity and/or shorter fibre lengths sustained quasi-periodic oscillations prevail, this degenerates into random bursting behaviour for longer fibres at higher pump powers. This physical model represents the interplay between the gain, weak external feedback, and nonlinear reflection. It explains how the complex dynamical behaviour arises in SBS in a single mode fibre due to the enhancement of the nonlinear refractive effect, which leads to periodic, quasi-periodic and chaotic emission, dependent on the pump power [25]. These observations are similar to those that have been seen in previous experiments. A model has been drawn up describing in the normalized form the slowly-varying amplitudes of the forward laser light, backward Stokes, acoustic wave and forward Stokes fields in [23, 25]. This considers electrostriction and intensity dependent refraction as contributing to the linear polarization.

The dynamical behaviour of the 2.87 μm laser described here can be interpreted based on these previous arguments as follows. For long fibre lasers long enough to absorb all the pump intensity, the back scattering and external feedback in the fibre is not strong enough to generate SBS and thus the laser operates under cw regime. The simultaneous pumping into the second end of the fibre (previously un-pumped length) provides the back scattering and the external feedback reflection will be enhanced, and thus the loss in the cavity increases. The level of losses determines the dynamic behaviour of the output. For small pump feedback the effect of SBS is small so that the dynamics are quasi-cw, increasing the pump feedback and decreasing the pumping into the other end results in enhancement of the SBS which increases the loss in the cavity and thus produces chaotic behaviour, i.e. random bursts of self-pulsation. Further variation of the loss, by changing the input and the feedback pumps, gives the possibility to producing regular self Q-switched pulses, with duration and peak power dependent on the fibre length and the bi-directional pumping power. Using shorter lengths of the fibre (i.e. short enough to let some pump power to be transmitted throughout the fibre) and at strong enough pump power will enhance the back scattered SBS and external reflected feedback from the un-pumped end of the fibre, thus a similar chaotic behaviour will be obtained, in agreement with previous observations in [25]. On the other hand, for weaker pump power, strong or weak quasi-cw output dynamics, depending on the strength of the pump power, will dominate, indicating that the SBS is too weak to create any significant chaotic behaviour in the output. For very short fibres the amount of back scattering and reflected power is high enough to generate strong SBS effects under all pump powers and produce chaotic dynamic behaviour. More detailed theoretical analysis of these results with a complete model is beyond the scope of this paper and will be described in further future work.

Another possible explanation to the previous experimental observation reported in this paper is the thermo-induced lensing stemming from ESA at lasing wavelength [12]. In the Ho^{3+}, Pr^{3+}-co-doped ZBLAN fibre laser the laser wavelength generated on the $^5I_6 \rightarrow {}^5I_7$ transition in Ho^{3+}, as shown in Fig. 8, can be reabsorbed again by Pr^{3+} ions as ESA inducing the $^3F_3, {}^3F_4 \rightarrow {}^1G_4$ transition [26]. The ESA cause a strong thermo-induced self-focusing inside the active fibre. The nonlinear mechanism causes the transition of the laser from cw-mode to self-pulsating mode operation. The detail study includes modeling of effects can be found in [12]. For very long fibre where the pump can absorbed totally in part of the fibre, the ESA absorption effect becomes weak since the fibre laser is 4-level laser and no enough population in $^3F_3$,$^3F_4$ to absorb the laser wavelength. However pumping both ends of the long fibre enhances the ESA of the laser wavelength. These because pumping both ends will increase the population in $^3F_3$,$^3F_4$ levels which result of decaying the excited ions from $^1G_4$, remembering that Pr^{3+} can absorb the pump power at 1064 nm and excited the ions from ground en-

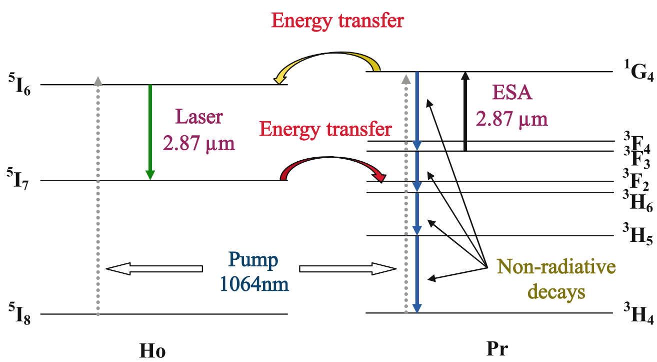

FIGURE 8 Partial energy levels term diagram for the Ho^{3+}, Pr^{3+} co-doped glass

ergy level to $^1G_4$ [26]. Equal pumping for the both end will enhance the thermo-induced self-focusing inside resulting in self Q-switching in the fibre. Fibre length around the optimum length will absorb more than 90% of the pump power thus at high pump power where $^3F_3$,$^3F_4$ levels populated, the effect of thermo-induced self-focusing appear clearly in fibre without second end pumping and result in self pulsing in the output. However, for short fibre even small pump power can populated $^1G_4$ thus populated $^3F_3$,$^3F_4$ resulting in strong ESA for laser wavelength and therefore strong thermo-induced self-focusing effects and that explain the self-pulsing behaviour of the output of very short fibres.

5 Conclusions

A range of dynamical outputs of a single-clad Ho^{3+}, Pr^{3+}-co-doped ZBLAN fibre laser pumped by Nd:YAG laser at 1064 nm has been observed and attributed to differing degrees of stimulated Brillouin-scattering effects (SBS) or to thermo-induced self-focusing cause by ESA of laser wavelength. The SBS arises due to back scattering, as well as the external reflection from the fibre ends. Bi-directional pumping enhances the SBS in a fibre longer than the optimum length of cw operation, and creates un-stable dynamic behaviour, ranging between quasi-cw to chaotic random pulse bursts to self Q-switching, depending on the powers pumped into both ends of the fibre. The pump wavelength can reabsorbed for Pr^{3+} ions and populated $^3F_3$,$^3F_4$ and thus enhance the absorption of laser wavelength from Pr^{3+} ions in the fibre. These lead to strong ESA and thus strong thermo-induced self-focusing effect especially at short fibres result in self pulsing effect. For long fibre where all the pump power absorbed the ESA is very small and only enhances by pumping the both ends of the fibre. A self Q-switched pulse train with a pulse duration of 767 ns, a peak pulse power of about 2.8 W and an average power of 183 mW, and with more than 80% pulse-to-pulse stability, has been obtained from a 13 m fibre with bi-directional pumping using powers of 4.5 W pumped equally into both ends. SBS is also enhanced by shortening the fibre which is apparent in the dynamic behaviour of the output for fibre lengths around the optimum length at high unidirectional pump power. This is apparent in the dynamic behaviour of shorter fibres, i.e. much shorter than the optimum length, at all pump powers down to the lasing threshold of the fibre.

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