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ARTICLE

Passively Q - Switched Linear Cavity IR Fibre Laser *via* Nonlinear Polarization Rotation

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Abstract: Setup for self-starting passive Q-switch operation of IR fibre laser *via* nonlinear polarization rotation (NPR) was demonstrated for the first time for linear cavity. A Q-switched pulse duration of ~ 600 ns, a maximum peak power of ~16 W and an average power of 408 mW have been obtained at 223 kHz repetition rate for 5.1 W pump power from 1319 nm CW Nd: YAG laser launched to ~ 2.78 m unidirectional single-clad Tm-doped silica fibre linear cavity using only flat polarizer and feedback mirror to induce NPR. The dependence of the fibre laser output characteristics on the polarization angle of the polarizer is also reported. However, self induced passive Q-switching in linear fibre laser cavities is only observed in fibres with angled cleaved ends and with lengths that are around the optimum length for CW operation.

Keywords: IR fibre laser, Passive Q-switching, Nonlinear polarization rotation, Linear cavity, Ring cavity.

PACS: Fiber lasers, 42.55.Wd, Q-switching, 42.60.Gd.

Introduction

Continuous wave (CW) and pulsed operations for fibre lasers operated near or amid IR have been demonstrated in various studies. The Q-switched fibre laser can be achieved actively or passively by various methods. These are by inserting: an acoustic optic or an electro-optic modulator inside the cavity of the laser [1 - 3] for actively Q-switched regimes or a saturable absorber (SA), such as transition metal doped crystal [4], FIrpic thin film [5], Europium Oxide (Eu_2O_3) [6] and semiconductor saturable absorber mirror [7], to achieve passive Q-switching operation. Q-switched fibre lasers using fibre-based SAs, such as carbon nano-tube [8 - 11], graphene [12], mismatch of mode field areas and a saturable-amplifier pump switch [13] and unpumped active fibre [14], have been also reported. Nonlinear polarization rotation (NPR) effect in fibre laser ring cavities with different designs has also been widely used to initiate and shape the pulses in Er-doped fibre lasers [16 - 18]. In fact, the NPR technique can produce intensity-dependent optical transmission by a self-phase modulation mechanism, thus providing an artificial saturable absorption effect in fibre lasers' cavity [17]. The saturable absorption strength can be adjusted by simply rotating a polarization wave plate. The NPR can also induce spectral filtering effect to achieve wave length tuneable passively mode-locked pulse [16]. Recently, a passively Q-switched all-fibre ring laser operating at 1949 nm, which is based on a nonlinear polarization rotation (NPR) technique using a 2 m long thulium-doped fibre and a 15 m long thulium-ytterbium co-doped fibre as active media, was reported [18]. However, self-start Q-switch operation *via* nonlinear polarization rotation (NPR) has not been achieved yet, to the best of our knowledge, in linear cavity fibre lasers.

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In this paper, a complete novel experimental demonstration and theoretical explanation of self-start Q-switching in linear fibre laser cavities were presented. A new and simple method to obtain stable self-start Q-switched output of a Tm^{3+}- doped silica fibre laser in linear cavity is illustrated. This method is based on inserting a plane polarizer inside the fibre cavity. The dynamic behaviour of the output, in this case, depends on the polarization angle of the polarizer and can vary between unstable self-pulsing to stable CW and finally to the requirement-stable self-start passive Q-switching by rotating the polarizer.

Experimental Techniques and Details

The experimental arrangement of the PQS is shown in Fig. 1.

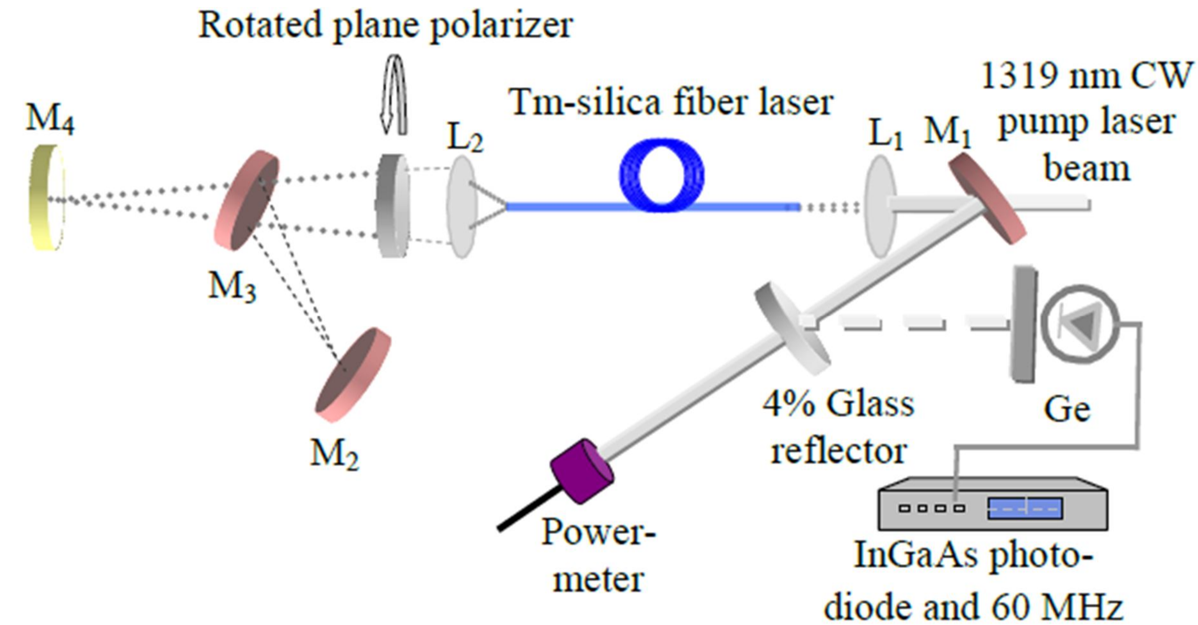

FIG. 1. PQS experimental arrangement of fibre laser pumped by solid-state laser, where M_1 is a 95 % T at 1.319 µm mirror, M_2 is a 45 deg. mirror that is HR at 1.8 - 2.1 µm and HT at 1.3 µm, M_3 is HR at 1.8 - 2.1 µm, M_4 is HR at 1.3 µm for feedback mirror and L_1 and L_2 are objective lenses.

The active medium of the cavity was a Tm-silica fibre laser cavity which operated at 2µm. The silica fibre had a core diameter of 16 µm and NA of 0.25 and was Tm-doped with a concentration of 1.1 % w. t. (7000 ppm molar). The silica fibre laser was pumped by 1.319 µm CW TEM_{00}, which is the output of Nd: YAG laser. A 7.5 mm focal length objective lens of NA = 0.25 was used to launch the pump light into the fibre. The measured launch efficiency was greater than 60 %. The cavity contained three high reflectance (HR) mirrors, M_1, M_2 and M_3. M_1 Mirror is highly transmitting (HT) at 1.3 µm and highly reflecting (HR) over the wavelength range of 1.8 - 2.1 µm. The mirror was positioned at 45 degrees to the beam axis and was used to separate the 2 µm beam from the pump. Another objective lens was used to re-launch the laser light reflected from the M_2 and M_3 mirrors into the distal facet of the fibre, where the mirror M_2 is HR over 1.8 - 2.1 µm and with high transmission (HT) at 1.3 µm, positioned at 45 degrees to the beam axis and mirror M_3 is 99 % HR over 1.8 - 2.1 µm. Therefore, the cavity was effectively formed by 4 % Fresnel reflection and two HR mirrors at 2 µm. Another mirror M_4, HR at 1.3 µm, was used to reflect back the pump light into the cavity in order to increase the cavity gain. A CaF_2 plane polarizer fixed to a rotation stage was inserted in-between the objective lens and the mirror M_2 to control the losses inside the cavity. The polarizer has a maximum transmission of ~80% at lasing wavelength and can operate over a wavelength range of 1- 2.4 µm with the degree of polarization > 98% at 2µm. The maximum power available was ~ 5.1 W and it reduced to ~ 4.8 W after the input mirror M_1 and the objective lens. The power launched into the fibre was ~ 3 W and the lasing threshold was about ~ 0.6 W. The maximum power available without the polarizer in the cavity was 523 mW without feedback from M_4 and ~ 600 mW with feedback, while the output dropped to 450mW when the polarizer was present in the cavity and feedback applied. Various fibre lengths were used of 1.95, 2.78 and 5.67 m and it was found that the optimum length for output power was in the range between 2.7 and 2.9 m. Careful cleaving of the ends of the fibre and accurate alignment have been adopted to achieve maximum power from the system. The operating parameters were measured, such as the relation between the input and the output powers, from which the launch efficiency, laser threshold and slope efficiency have been determined. The output with a centre wavelength of 1.95 μm was detected by a photodiode (Hamamatsu G8422 - 05) with a cut-off frequency of 80 MHz and a rise time of 4.37 ns.

Passive Q-Switching Operation in Linear Cavity

The temporal profile of the output of the 2.78 m Tm doped fibre laser without the polarizer placed in the cavity showed that the output was a stable CW when the un-pumped end of the fibre was cleaved normally with respect to the fibre optical axis (Fig. 2a), while the output became quasi-CW when the fibre was angled cleaved with $\theta \approx 8$ deg. with respect to the normal on the optical axis of the fibre (Fig. 2b). The maximum output power for both cases was 530 mW. When feedback from M_4 mirror was applied, the quasi-CW output changed to self-pulsing with a maximum power of 572 mW for both angled cleaved fibre (Fig. 2c) and normally cleaved fibre (Fig. 2d).

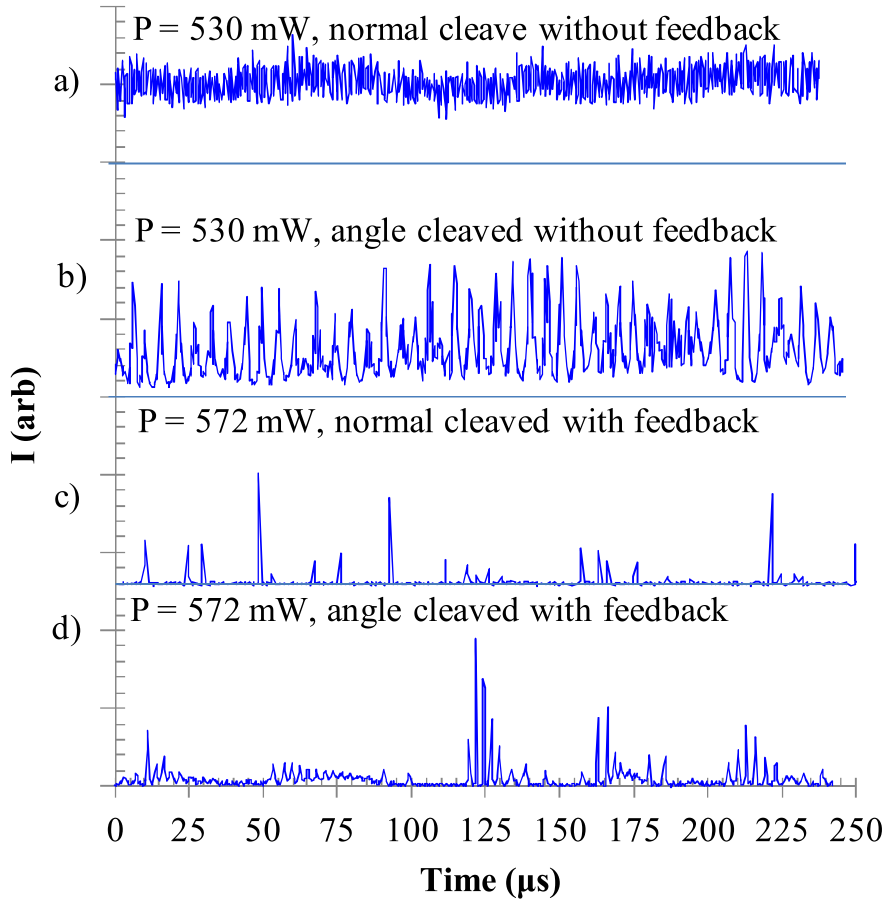

FIG. 2. Temporal behaviour for several cavity arrangements without in-cavity polarizer: a) normal cleaved fibre, blocked feedback pumping from mirror M_4 b) angled-cleaved fibre, blocked feedback pumping from mirror M_4, c) feedback from mirror M_4 for angle cleaved fibre d) feedback from mirror M_4 for normally cleaved fibre.

With the normally cleaved fibre, the two Fresnel reflections for both ends of the fibre (i.e., 4 % reflections) were enough to create about 220 mW self-lasing output in the fibre, which increased to 530 mW when feedback was provided from both the high-reflectance mirrors M_2 and M_3. This output power varied between a minimum power of 267 mW followed by a maximum power of 442 mW and then another minimum of 358 mW when in-cavity polarizer was set at angles of θ = 0, 45 º and 90º. The temporal profile of the output beam in Fig. 3 shows no significant changes in CW operation related to the changes in the rotation angle of the polarizer. However, it is clear from Fig. 3 that the fluctuation of the CW temporal profile is output power-dependent.

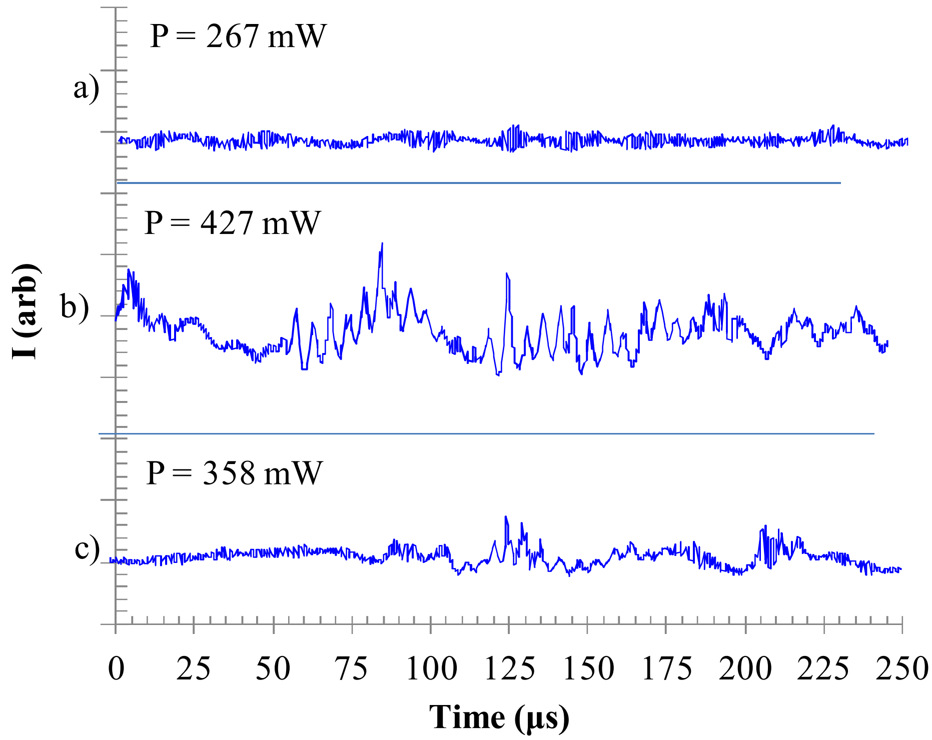

FIG. 3. Laser intensity time dependence for normally cleaved fibre for 3 orientation angles Φ of the intra-cavity polarizer. a) Φ = 0˚, b) Φ = 45˚, c) Φ = 90˚.

When the fibre was angled cleaved at an angle equal to ~ 8º, feedback from M_2 and M_3 mirrors was required in order to generate laser action in the cavity. With the cube polarizer in the cavity and set to give minimum output power, a power of 109 mW CW was obtained, Fig. 4a. Rotating the polarizer resulted in an increase of the output power, while no significant change was found in the temporal behaviour of the laser output until the output increased to 356 mW and the temporal behaviour now was quasi - CW, Fig. 4b. Further rotation of the polarizer leads to further increase in output power and the temporal dynamics of the output are now unstable with a self-pulsing output power of 409 mW, Fig. 4c. Increasing the rotation angle further, the output power reduced again, but became more stable; i.e., CW output with a maximum power of 405 mW, Fig. 4d. A minimum value of output power of 300 mW was obtained and the output at this power was unstable self-pulsing, Fig. 4e. The output power increased on further rotation of the polarizer until it reached a maximum power of ~ 435 mW and the output was now a stable passive Q-switched pulse train with a peak power of 12.7 W and a pulse duration of 733 ns at 211 kHz repetition rate, Fig. 4f. Further rotation of the polarizer decreased the output power again until another minimum was reached and the output became unstable self-pulsing.

Setting the polarizer to achieve the maximum power gave a temporal profile of the output which was passive Q-switching. The input power was varied down to the threshold lasing of the system. Fig. 5 shows that self-Q-switching occurred at all applied pump powers.

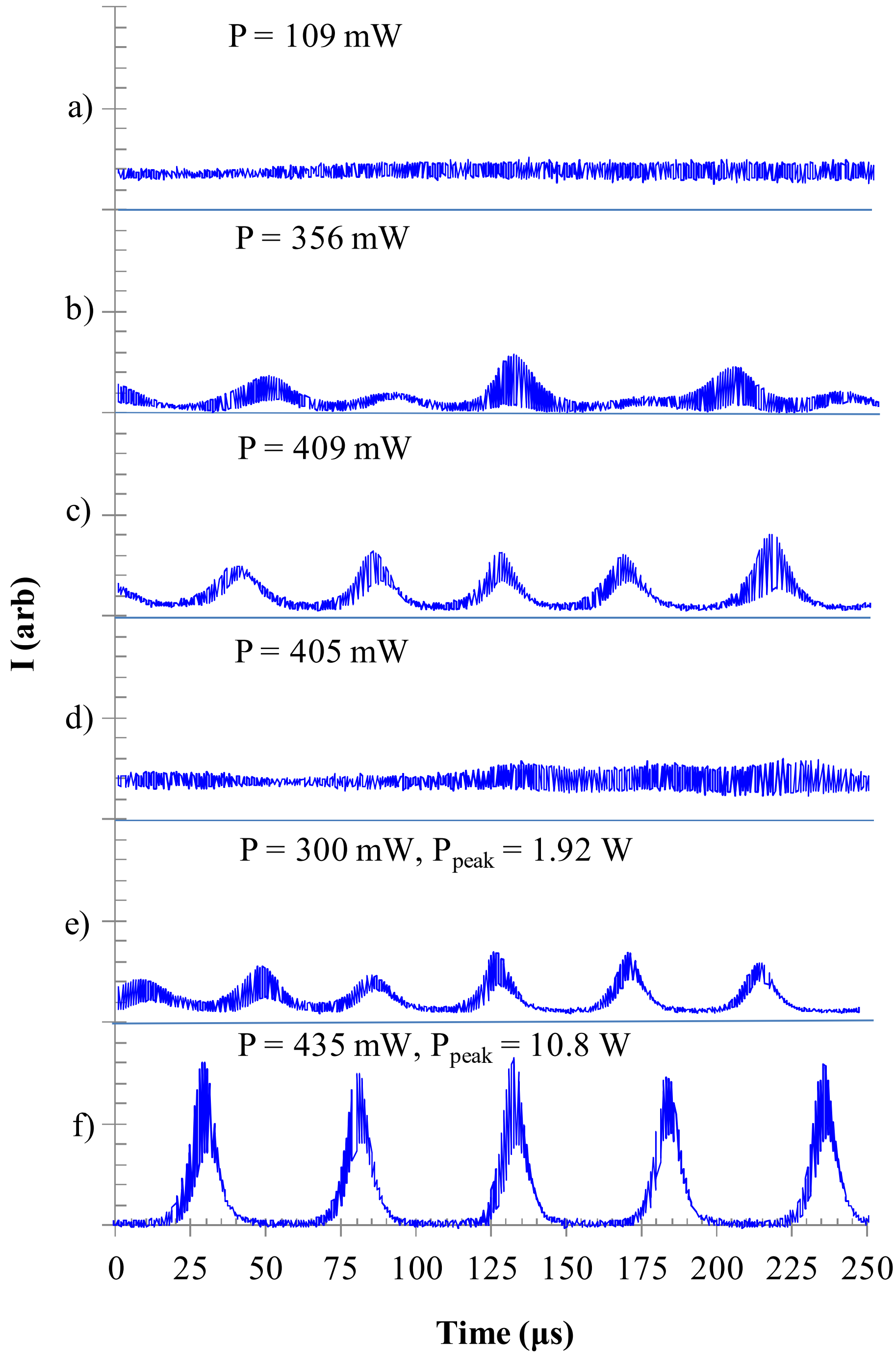

FIG. 4. Dynamics of normally cleaved fibre end with different orientation angles of the intra-cavity polarizer, resulting in: a) CW operation at minimum output power, b) Quasi-CW operation at higher power, c) Self-pulsation at maximum power, d) CW when the power is decreased, e) Chaotic self-pulsation when the output power decreased to the minimum, f) Self-Q-switching when the power is increased to maximum again.

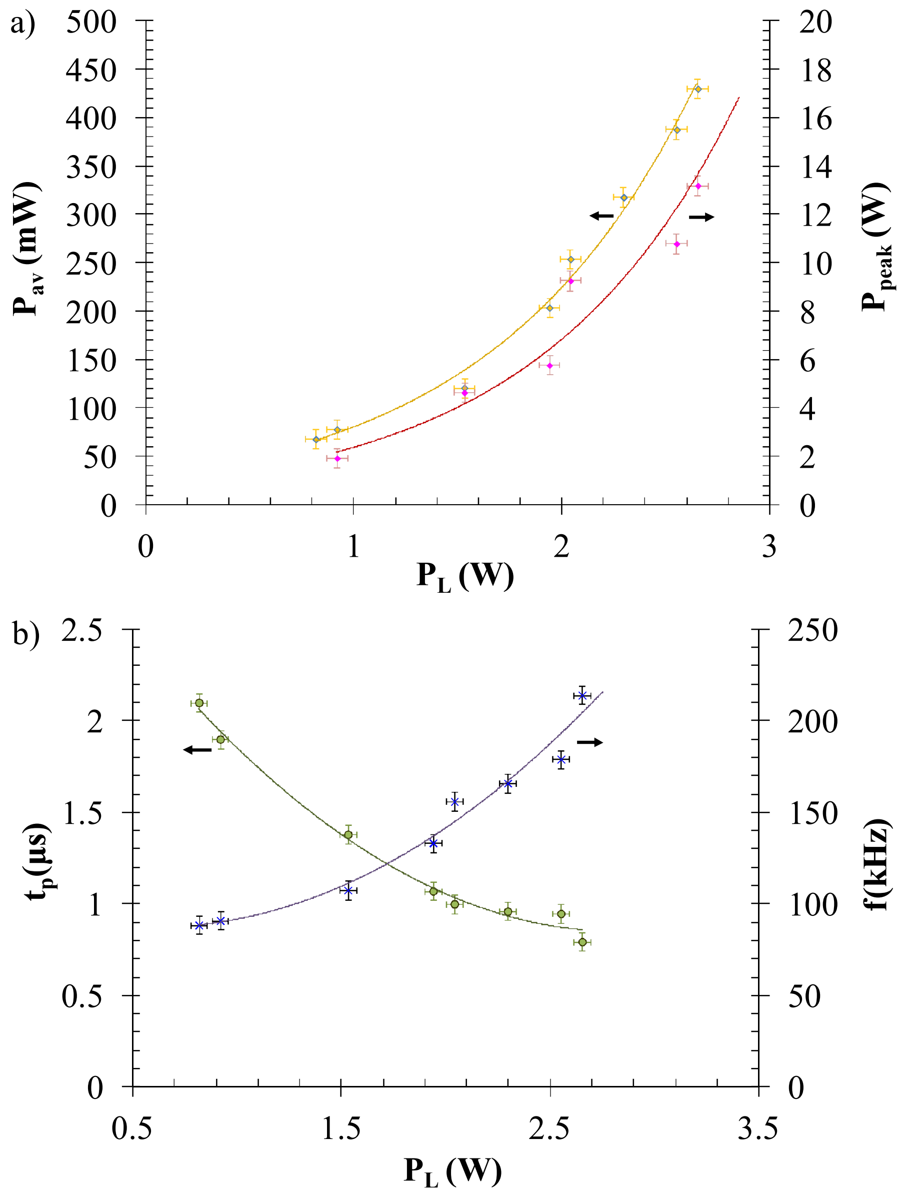

FIG. 5. Self-Q-switching for various pump powers down to the threshold pumping.

The relation between the average output power and the peak power of the Q-switched pulses as a function of launched power is shown in Fig. 6a. Both average power and peak power increased with increase in the launched power. Additionally, Fig. 6b shows that the frequency of the self-start Q-switched pulses increased while the pulse duration decreased for increase in launched power. These results agreed with ones represented in a previous work that has been done in ring cavity for the same wavelength [18].

The dependences of the passive Q-switched profile and the dynamics of the fibre output on the fibre length were investigated. For a short fibre, 1.95 m (Fig. 7a), the dynamics was quasi -CW when the polarizer has been adjusted to give maximum power extracted from the cavity. However, self-start Q-switching or stable CW has not been observed at any rotation angle of the polarizer. Similarly, a long fibre of 5.67 m showed no effect of rotating the angle of the polarizer on the dynamic behavior (Fig. 7c). The output in this case was CW at any rotation angle of the polarizer. In contrary, a ~16 W maximum peak power and 408 mW average power self-start Q-switching pulse train with duration up to ~ 600 ns at ~ 223 kHz repetition rate (i.e., 4.48 µs time interval between the pulses) had been observed for an optimum fibre length of 2.78 m when the system was operated in Q-switch regime (Fig. 7b). Self-mode-locking with ~ 100 % modulation depth was also perceived within the observed Q-switching pulses.

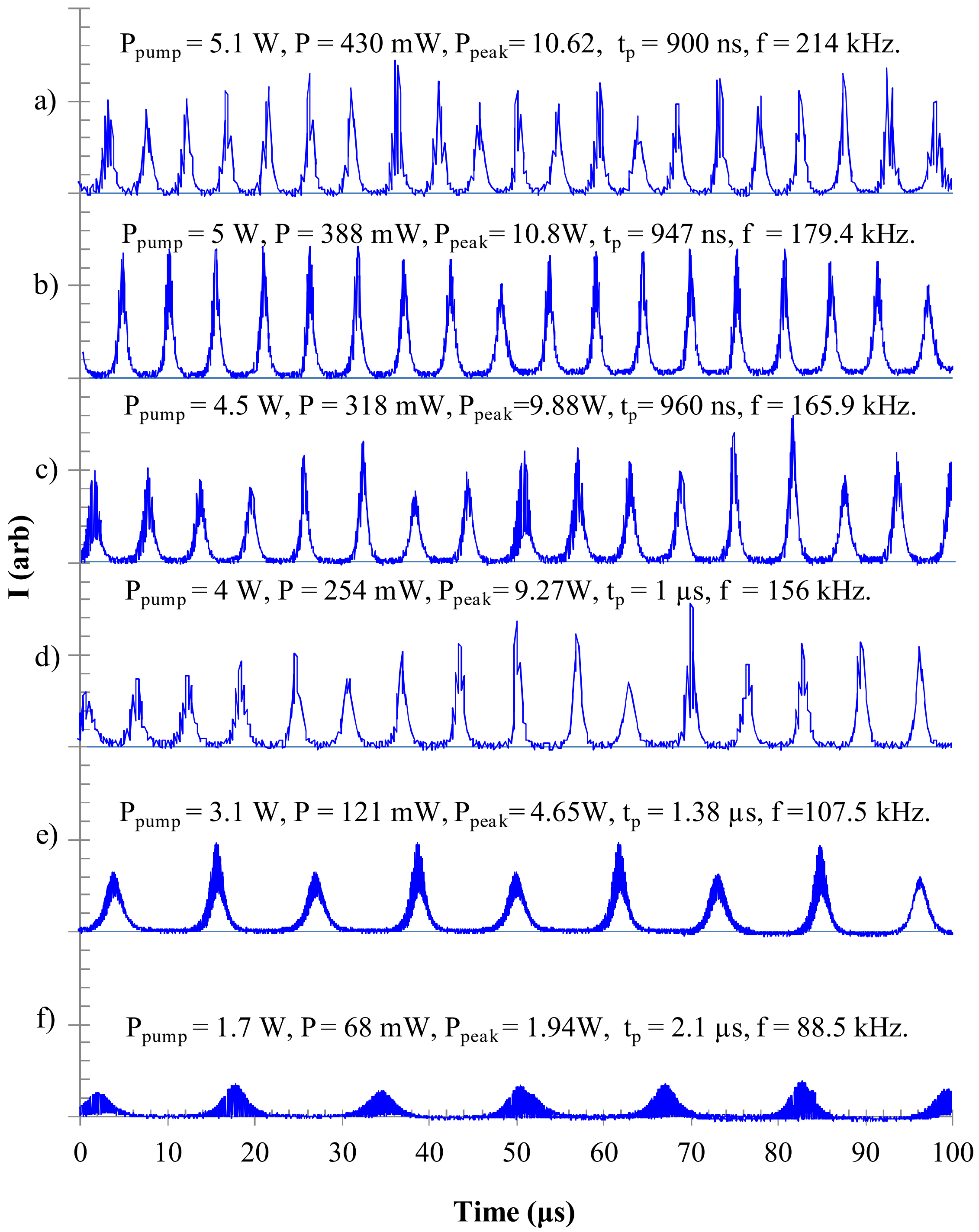

FIG. 6. Output characterization for increasing launched power in the self-start Q-switched regime. a) Average output power and individual peak pulse power as a function of launched pump power, b) The frequency and the pulse duration as a function of launched pump power for fibre length of = 2.78 m.

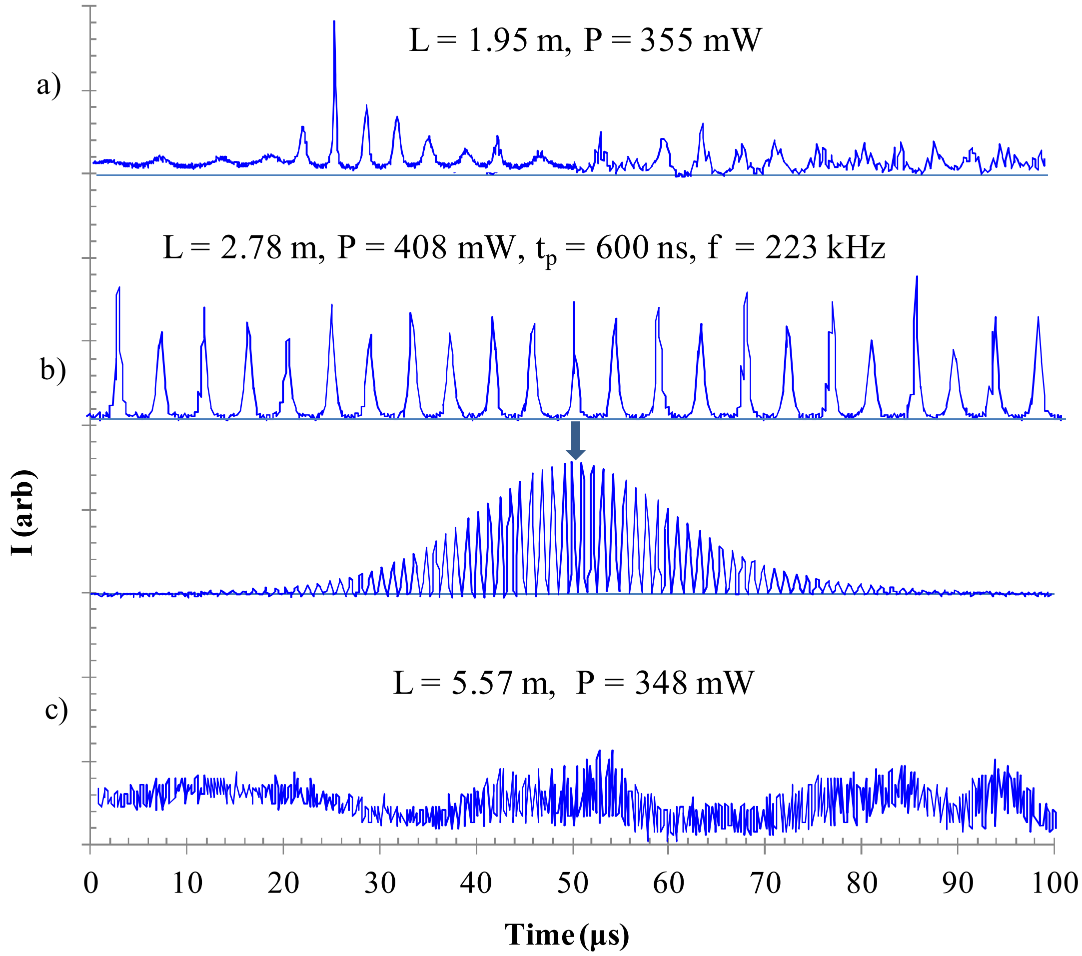

FIG. 7. Temporal evolution of the intensity for: a) Minimum output from 1.95 m fibre, b) Maximum output from 2.78 m fibre and the self-mode-locking inside the pulse, c) Minimum output from 5.67 m fibre.

The dependence of the dynamics of the output on the orientation angle of the polarizer in this investigation is summarized in Fig. 8. However, the two consecutive lower peaks in all parts of Fig. 8 have different amplitudes, which indicates that the intra-cavity laser light beam is more likely elliptically polarized with large and small components (radii) parallel to the axis of the fibre. However, it can be deduced from Fig. 8 that at an orientation angle of the polarizer equal to 90º, only one component (i.e., the larger component as the low peak in this case is higher than the lower next one) passes through the polarizer and is launched back to the fibre and because it was already parallel to one axis of the fibre, only one polarization will propagate inside the fibre resulting in CW output. The same scenario will repeat after 90º (i.e., for an orientation angle of the polarizer at 180º), while the smallest will pass through the polarizer to launch back to the fibre resulting in CW output, but with lower power compared with the previous case. In contrast, if the polarization angle of the launched back beam is not parallel to the one axis of the fibre (i.e., the orientation angle of the polarizer should be between m πº and (2m+1) π/2º, where m is an integer number), the linear polarization will split into two components when it propagates inside the fibre and the beam becomes elliptically polarized with a different angle than the initial one, resulting in NPR. The effect of NPR increases as the orientation angle of the polarizer increases until reaching the maximum effect at an angle equal to m π/4, where the two components of linear polarization of the launched back beam on the entrance face of the fibre become equal. The output in this case is more likely QS.

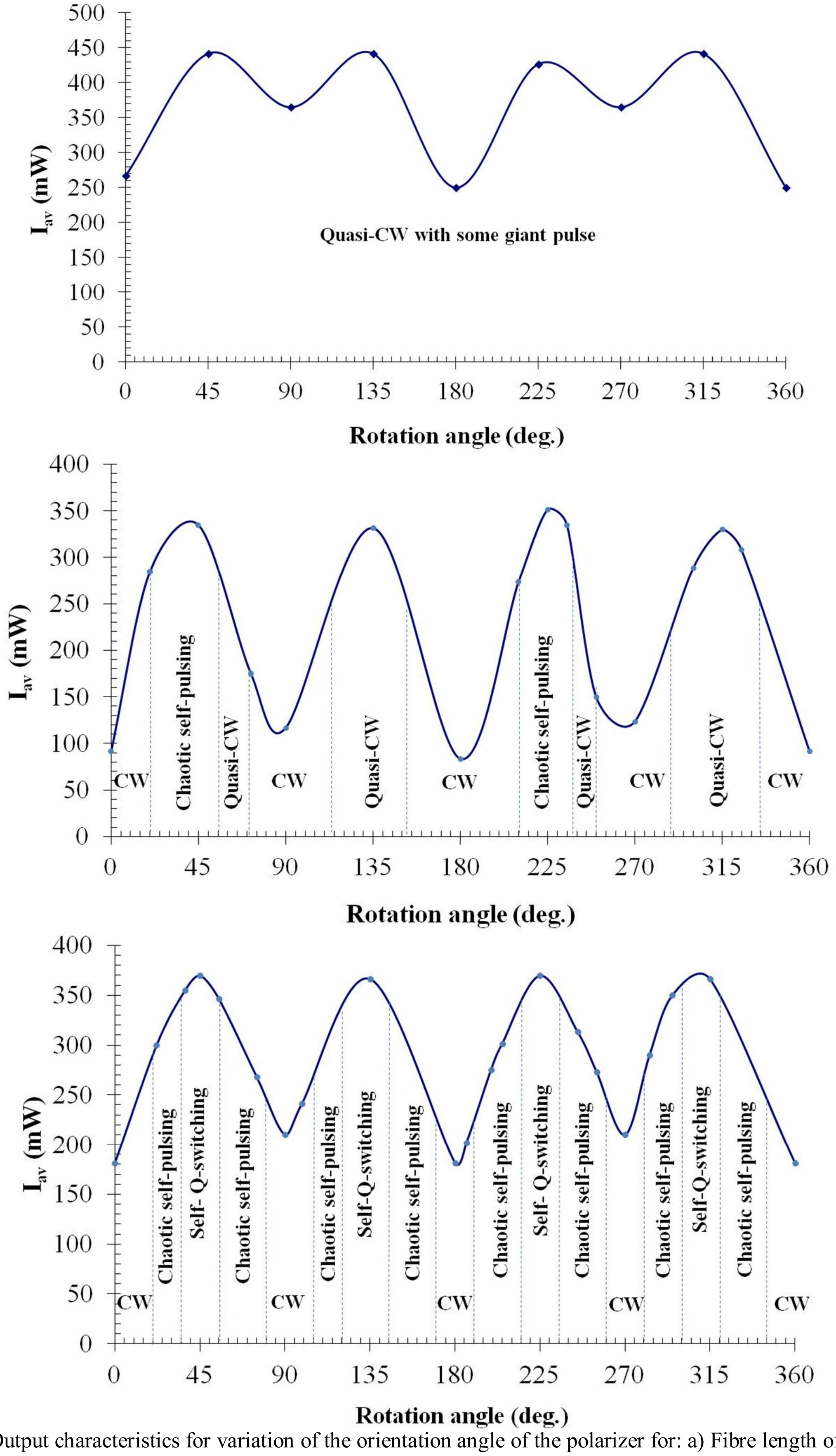

FIG. 8. Output characteristics for variation of the orientation angle of the polarizer for: a) Fibre length of ~ 2.9 m (which resulted in optimum output power) with flat cleaved end, b) Fibre length of 2.5 m with angled cleaved end. c) Fibre length of ~ 2.8 m (which resulted in optimum output power) with angled cleaved end.

Discussion

NPR is a phenomenon that results from the changes in the direction of light polarization inside the laser cavity. These changes are due to self-phase modulation (SPM) and cross-phase modulation (XPM) in addition to some birefringence of the fibre [19]. Those nonlinear effects which cause rotation of light in fibre were exploited to enable intensity modulation mechanism in the laser cavity. The NPR - based Erbium - doped fibre laser (EDFL) relies on the Kerr effect that creates inside the fibre in conjunction with an optical isolator to produce a pulse by setting the initial polarization state to elliptical. This elliptical state can be resolved into right- and left-hand circular polarization components of different intensities when launched to the fibre. As a result, an elliptically polarized pulse will have its x and y components experience different phase shifts, thus rotating the polarization ellipse.

The light separates inside the fibre into two orthogonal polarized lights; E_x and E_y. After passing through the fibre, both E_x and E_y accumulate nonlinear phase shift due to the SPM and XPM effects in the fibre. The angle of polarization can be changed from α_1 to α_2 as the light propagates through the fibre. Here, α_1 is the angle between the polarization direction of the laser beam and the fast axis of the fibre and α_2 is the angle between the fast axis of the fibre and the polarizer direction (Fig. 9). The beam transmission is described using the following equation [20, 21]:

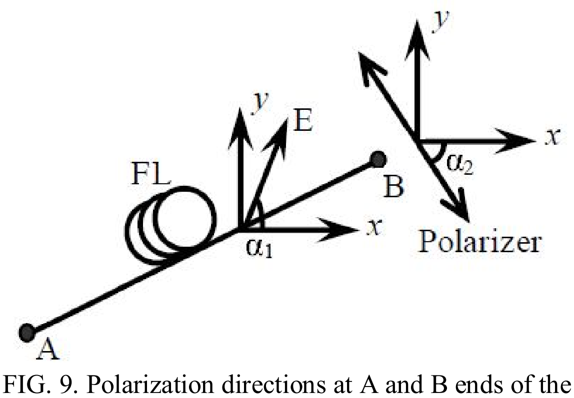

FIG. 9. Polarization directions at A and B ends of the fibre laser (FL) for NPR operation, where E: electrical vector of laser beam; x and y: fast and slow axes of the fibre, respectively [20].

$$T = cos^2\alpha_1 cos^2\alpha_2 + sin^2\alpha_1 sin^2\alpha_2 + (1/2)\, sin2\alpha_1 sin2\alpha_2 \cos(\Delta\varphi_L + \Delta\varphi_{NL}) \quad (1)$$

where $\Delta\varphi_L$ is the linear phase shift from modal birefringence and $\Delta\varphi_{NL}$ is the nonlinear phase shift contributed by both SPM and XPM effects. $\Delta\varphi_L$ *and* $\Delta\varphi_{NL}$ are calculated from:

$$\Delta\varphi_L = (2\pi L/\lambda)\,(n_y - n_x) \quad (2)$$

$$\Delta\varphi_{NL} = (2\pi n_2 PL/\lambda A_{eff})\, cos2\alpha_1 \quad (3)$$

where n_y *and* n_x are the refractive indices of the respective fast and slow axes of the optical fibre, L is the fibre length, λ is the operating wavelength, n_2 signifies the nonlinear refractive index, P is the instantaneous peak power of the input signal, while A_{eff} is the effective core area. The angle α_2 can be manipulated by rotating the polarizer to obtain the maximum modulation, which makes the system act as an artificial saturable absorber, which leads to PQS. The PQS starts to weaken and disappear if the polarization angle of the incident beam differs from $\pi/4$ in respect to fibre fast axis. The reason for this is that decreasing or increasing the rotation angle to approach 0˚ or $\pi/2$ will minimize the modulation term (third tem) in Eq. 1 and the output is then quasi - CW and becomes CW for a rotation angle making α_2 equal to 0˚ or $\pi/2$ and the third term equal to zero.

However, another experiment was carried out using Tm fibre laser linear cavity with only an internal plane polarizer to induce the self-starting of PQS operation in fibre laser. Before starting conducting the second PQS experiment, it was too important to stabilize the output of the fibre. Two different methods to stabilize the output of a Tm-doped silica laser have been developed here before doing PQS experiment. The first method relied on enhancing the feedback from the un-pumped end of a unidirectional pumped fibre by using a normally cleaved fibre end, while the second method was based on using an angled cleaved fibre and modulating, the losses inside the cavity with an intra-cavity polarizer. The 4 % reflection from the fibre end created self-lasing in the fibre even without using any HR coupler. This self-lasing helped stabilize the output and make any extra losses in the external cavity formed by an intra-cavity polarizer or any other sources insufficient to affect the dynamic behaviour of the output.

The self-lasing power perhaps plays the same role as using resonant pumping [22] to stabilize the output of the fibre laser. However, re-launching the pump power again to the cavity using mirror M_4 enhances both the saturable absorber effects in the un-pumped end of the fibre and the pump noise which might be reasons for unstable self-pulsing operation of the laser [23, 24]. Angled cleaving of the distal facet of the fibre suppresses any feedback and stabilizes the output and as a consequence the output becomes unstable-self-pulsing. With an angled cleaved fibre, the cavity is more sensitive to any extra modulation that occurs in the cavity by external modulations. When the polarizer is placed in the angled cleaved fibre cavity, the loss in the cavity is increased; these losses are due to two factors, a) the transmission losses of the polarizer substrate material, b) polarization losses dependent on the angle between the polarizer and intra-cavity laser, assuming that the laser output generated by the fibre is generally partially polarized. The unequal lower peaks in Fig. 8 indicate that this fibre is birefringent and the fast axis is in y direction (i.e., at $\pi/2^{\circ}$). However, the horizontal polarization is more enhanced when the fibre end angle is cleaved, which will improve more with an angle closer to Brewster's angle. On the other hand, when the partially polarized beam exiting from the far end of the fibre cavity passes through the polarizer, it becames perfectly polarized at $\pi/4^{o}$. The beam is then reflected back to the polarizer by the 2 rear mirrors and can pass through the polarizer without any change, as there is no change in the polarization direction. The polarized beam is then launched back to the fibre and because of the polarization direction at $\pi/4^{o}$ in respect to fibre axis, the beam splits inside the fibre to two equal perpendicular components. As before in the ring cavity, for an angle of $\pi/4^{o}$, the transmission from Eq. 1 will be:

$$T = -\left(1 + (1/2)\cos\left(\Delta\varphi_L + \Delta\varphi_{NL}\right)\right) \qquad (4)$$

This equation indicates that the modulation in this case is maximum, which induces PQS operation. Since the PQS operation depends only on the rotation angle phenomenon, it will be pump power-independent and that is what the experimental studies confirm in Fig. 5. Rotating the polarizer by another $\pi/4^{\circ}$ deg. (i.e., the direction of the polarizer in this case is at 0 or $\pi/2^{\circ}$) allows the polarization to transmit through the polarizer after second path (i.e., after being reflected from the rare mirror) with a direction at an angle of 0 or $\pi/2^{\circ}$, which will be parallel or perpendicular to the optical fibre axis and therefore only one beam propagates inside the fibre and the modulation term in Eq. 3 will equal zero resulting in pure CW. The temporal evolution of the output then favours an unstable output, ranging between quasi - CW and self-pulsing, depending on the angle between the laser and the plane surface of the polarizer, as shown in Fig. 8b and c. It is clear that the scenario repeats itself with the rotation of the polarizer by $\pi/2^{\circ}$ degrees and again the output changes depending on the interference from CW to quasi - CW with chaotic self-pulsing and PQS to quasi - CW with chaotic to CW again. In contrast with the first experiment, self-lasing occurs in this type of fibre for flat cleaved end. Fig. 8a shows no PQS for this case and indicates that it is important to eliminate any scattering and self - lasing beams to be created in the cavity in order to achieve the polarization rotation state that is necessary to produce PQS. This can be done by angle cleaved fibre laser end. However, self-start passive Q-switched pulsed output was obtained at nearly optimum length of the fibre, as the very long fibre will affect the polarization direction and lead to more un-polarized beam at its far end, while high dynamics in the short one due to strong pumping will also affect the polarization state of the beam and prevent complete modulation. Finally, no PQS is obtained when a horizontally polarized 1064 nm laser pumped this fibre. Pumping the fibre with polarized 1064 nm laser light resulted in stable CW output even with an angled cleaved fibre. Thus, it can be deduced that pumping with polarized light or adjusting the polarization in the linear cavity so that only one polarization propagates inside the fibre, might play a role in reducing any loss due to Brillouin scattering or any other scattering effects in the fibre that prevent PQS operation (no modulation loss can take place inside the fibre).

Conclusion

NPR technique was applied to create a PQS train pulse in linear fibre laser cavity. A train of pulses with time duration of 4.48 μs, pulse width of around 600 ns, average power of 408 mW at 1.9 μm from Tm-DFL pumped by 1319 nm a Nd: YAG laser was obtained using NPR by means of only a plane polarizer. The comparison between the two techniques confirmed that starting PQS process depends on loss variation following nearly the same scenario depending on the polarizer or half-wave plate angle. It was demonstrated that, at a polarizer or half-wave plate angle of π/4º in respect to fibre axis, the elliptical polarization of the re-entering beam will rotate inside the fibre causing strong losses of modulation that lead to start PQS. However, other regimes like chaotic self-pulsation, quasi - CW or CW will take place for other rotation angles.

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