Volume 14, Number 3, 2021. pp. ??-??

Jordan Journal of Physics

ARTICLE

Fundamental and Harmonic Self Mode-locking in Mid IR Heavily Doped Fiber Lasers

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Doi:

Received on: ??/??/????; *Accepted on: ??/??/????*

Abstract: Harmonic self mode-locking effects are observed in heavily doped fiber lasers operating near 3 µm. The temporal profiles for the output of an Er-ZBLAN fiber laser operating at ~2.7 µm and a Ho, Pr-ZBLAN fiber laser operating at ~2.87 µm are reported. Stable second harmonic mode-locking is observed in the Er-ZBLAN fiber laser under 970nm pumping for an Er concentration of 50000 ppm, while unstable harmonic mode-locking of order of between 1-1/7 times the round cavity round trip time was observed for the higher concentration of 80000 ppm and for all pump powers. Unstable harmonic mode-locking is observed in the Ho, Pr-ZBLAN fiber laser when pumped at 1064nm, for fiber lengths up to 13m and for all pump powers. The experimental mode-locked pulse train periods are found to be consistent with theoretical analysis. The origin and properties of harmonic self mode-locking in heavily doped ZBLAN fiber lasers operated near 3 µm are discussed.

Keywords: Er-ZBLAN fiber laser, Ho, Pr-ZBLAN fiber laser, Self mode-locking, Harmonic self mode-locking.

PACS: Fiber lasers, 42.55.Wd, Mode locking, 42.60.Fc.

Introduction

Pulsed Fluoride glass fiber lasers of various configurations have exhibited both continuous wave (CW) and pulsed output at power levels in the 2W range at wavelengths in the 2.7-3 µm spectral region, that can be useful for numerous medical, industrial and research applications. These fiber lasers have potential advantages of being flexible (the laser output can easily be guided into difficult regions), compact, efficient, reliable and low cost compared with other bulk lasers. In addition to all these advantages, the temporal profile of these fibers is very rich in effects and their nonlinear properties make them attractive for ultra-short pulse production which might be useful for medical and surgery, sensing, materials processing with high moisture content, textile manufacturing and general research applications. Ultrashort pulse generation in lasers generally relies on mode-locking by amplitude modulation (AM) or frequency modulation (FM) at the cavity round trip frequency. These effects can be induced actively or passively in the cavity. However, some cavities incorporate self-focusing or extra-nonlinear effects resulting in self mode-locking (SML) [1,2]. SML has been reported in gas [3], dye [4], and solid state (particularly the Ti-sapphire) and ruby lasers [2,5]. Self mode-locking in CW or pulsed operation has been reported for many fibers operating between 1 to 2 µm, these include neodymium [6,7], ytterbium [8], erbium [9 -11], thulium-silica [12 -14], thulium-holmium [15] and thulium-ZBLAN [16]. The details of the previous observations can be found in [12]. Self-locking in fiber lasers has been attributed to either the possible existence of Brillouin scattering in the output of the pulsed fiber laser [17 - 19], the optical Kerr

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effect and the presence of self-phase modulation [6], frequency pulling contribution for the doped material [7] or the existence of saturable absorption in the fiber core [12] as a result of the creation of colour centres during the up-conversion lasing [16].

Harmonic mode-locking is another interesting feature which was reported in some fiber lasers where additional pulses can be observed located in-between the train of the phase-locked pulses when the fiber is passively mode-locked [20, 21]. Harmonic mode-locking is also observed in stimulated Brillouin scattering (SBS) fiber lasers due to hole burning in the spectrum of SBS in optical fibers [22]. Harmonic mode-locking can be used to scale up the repetition rate of femtosecond fiber lasers which may be very useful for some applications, although the time jitter of the harmonic mode-locked pulses around their average positions might be relatively high. The repetition rate of the harmonic mode-locking can be simply changed by variation of the pump power level to the fiber cavity [23]. Harmonic mode-locking is generally observed in soliton fiber laser with negative group velocity dispersion [24] and is interpreted as being due to a repulsive force between the pulses that is generated by phase effects in saturable absorption [25], as well as the recovery dynamics in the saturated gain medium [26]. Additionally, the interaction of the soliton pulses with a small oscillating continuum in the cavity can produce repulsive and attractive forces between the pulses leading to harmonic mode-locking. Acoustic resonance of the fiber at subgigahertz frequencies leads to further stabilization of the harmonically mode-locked train and particularly can reduce the time jitter to very small values [27, 28].

In this study harmonic self-locking is observed in fibers emitting near 3μm. Self-mode locking has not been reported previously in fibers emitting in the 3μm spectral region and harmonic mode-locking in general has not so far been observed in any fibers which incorporate self mode-locking. The repetition rate and the stability of the mode-locking are established to be dependent on the concentration of the dopant as well as the length of the fiber, while no significant dependence is observed on the strength and condition (CW or pulsed) of the pump on stability and the repetition rate of the harmonic self-locking.

Experimental Techniques and Measurements

The following fiber lasers were used for these studies:

1) A double-clad Er-doped ZBLAN fiber laser that has a rectangular-shape to match the shape of the pump beam of a high power 970 nm diode laser and promote cladding-to-core coupling, 40 mm diameter core which supported multi transverse mode operation, core numerical aperture (NA) of 0.12, first clad NA of 0.5, a rectangular first cladding with a dimensions of 150 and 200 mm. Two different doped core concentrations have been used, 50000 ppm molar for a fiber length of 7.3 m and 80000 ppm molar for a fiber length of 11.3 m.
2) A single-clad Ho, Pr doped- fluoride fiber had concentrations of 30000 ppm molar Ho and 3000 ppm molar Pr, a core diameter of 15μm, a numerical aperture of 0.13, an intrinsic loss of ~30 dB/km at 800 nm and supported single mode operation. Laser action in this fiber had previously demonstrated [29, 30].

Observations of Harmonic-Locking in Double-Clad Er-Doped ZBLAN Fiber Lasers

The experimental arrangement is shown in Fig. 1.

The Er-doped fiber laser was pumped by a 30 W diode laser operating at 970 nm. The diode provided both CW and square pulse pumping with minimum duration and period of 1 ms. The pump was launched to fiber via objective lens with numerical aperture (NA) of 0.25. The fiber was butted to the mirror, highly reflecting at the lasing wavelength and high transmittance at the pump wavelength. The distal facet of the fiber was butted to a Ge filter to reflect the pump wavelength, as well as to provide feedback to the cavity. The temporal behaviour of the output was monitored by an InGaAs photodiode (Hamamatsu G8423-03) with a cut-off frequency of 60 MHz and a rise time of ~ 6 ns. The photodiode has a cute-off wavelength of 2.6 μm and was used as a two-photon absorption detector; however, a Ca_2F lens was used to focus the light into the detector and thus increase the gain.

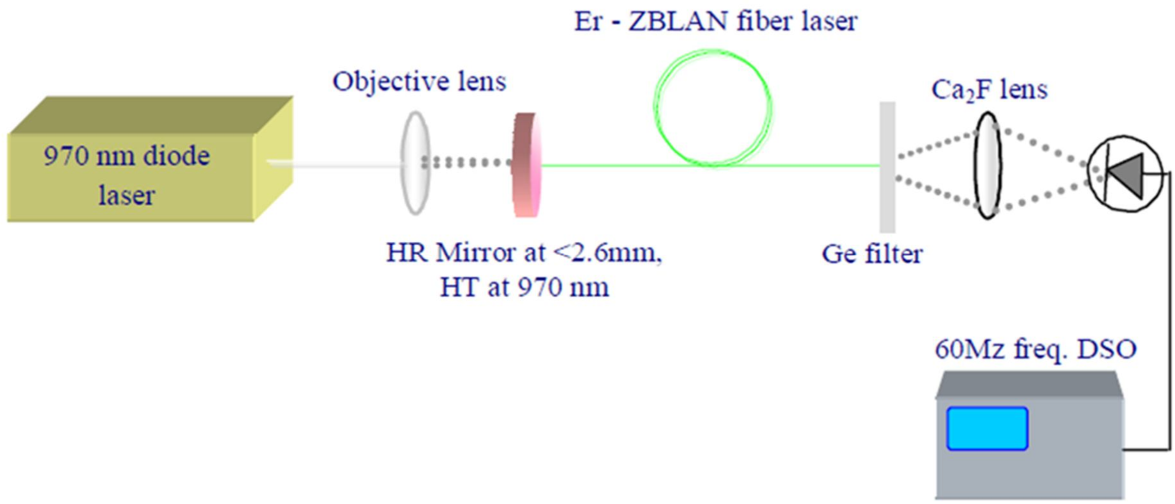

FIG. 1. Experimental arrangement for diode pumped Er-doped ZBLAN fiber laser. (DSO-digital sampling oscilloscope).

Cutback experiments showed that more than 82 % of the pump light was launched into the fiber, which resulted in a maximum power of 300 mW with ~18 % slope efficiency after the threshold of 100 mW launched power, for a fiber length of 7.6 m with a dopant concentration of 50000 ppm. A maximum power of 190 mW with ~11% slope efficiency after the threshold of 300 mW was produced for a fiber length of 11.3 m with a dopant concentration of 80000 ppm. The temporal output for the 50000 ppm Er-doped fiber showed that at low pump power, near the threshold, the output was self-pulsing with a chaotic pulse burst, each of these pulses consisted of a train of small pulses with a time period between pulses of 37.5 ns, which is equal to the half the cavity lifetime T_R. At higher pump power, the output changed into CW, and a train of small pulses was also observed within the output at the same repetition rate. Thus there was no significant effect of pump power on the generation of the train of short pulses or on changes in its repetition rate, the pulse train appeared to be almost stable for all pump powers as shown in Fig. 2.

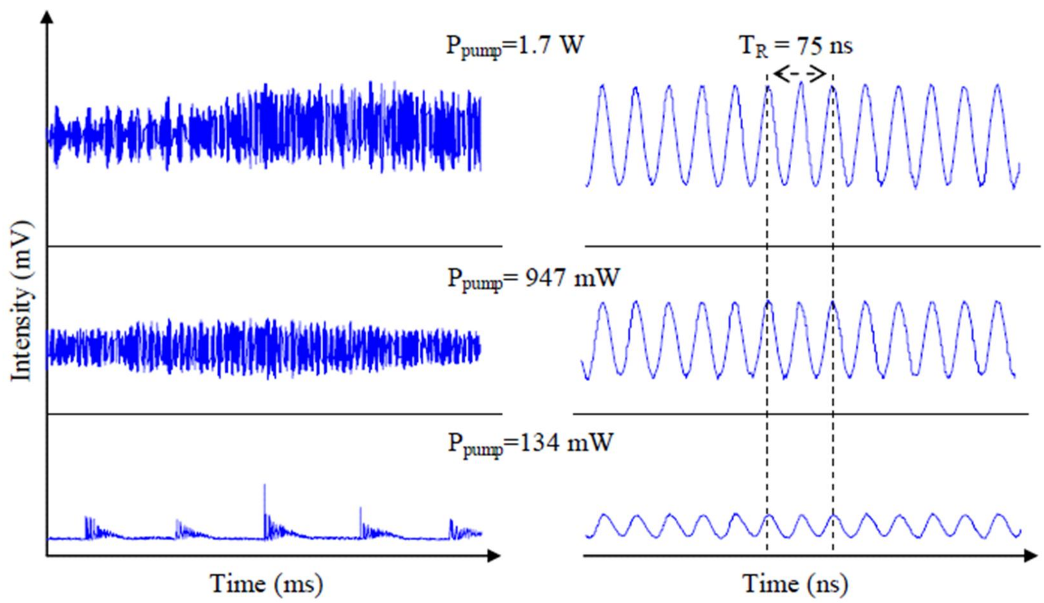

FIG. 2. Self-locking observations in the output of Er-doped ZBLAN fiber laser with concentration of 50000 ppm molar, at various pump powers. The fiber length was 7.3 m and the self mode-locking occurred at half the cavity round trip time T_R.

More investigations were carried out using longer fiber about 11.3 m, with a higher concentration of 80000 ppm molar. The temporal output showed similar observation to the first experiment but with an unstable train of short pulses and with more harmonic order. Fig. 3 shows that for all pump powers down to the threshold, the train of short pulses mainly consisted of a train of short pulses with a time interval between pulses matching the cavity round trip time T_R, and after a short time more pulses started to develop in between the main pulses resulting in a train of short pulses with period time varying between T_R - 1/4 T_R and pulses became weaker for time periods between 1/5 T_R – 1/7 T_R.

However, the train of short pulses was also seen in the pulsed output of the fiber when pulsed pumped with 1ms on and 1ms off pulses, as in Fig. 4.

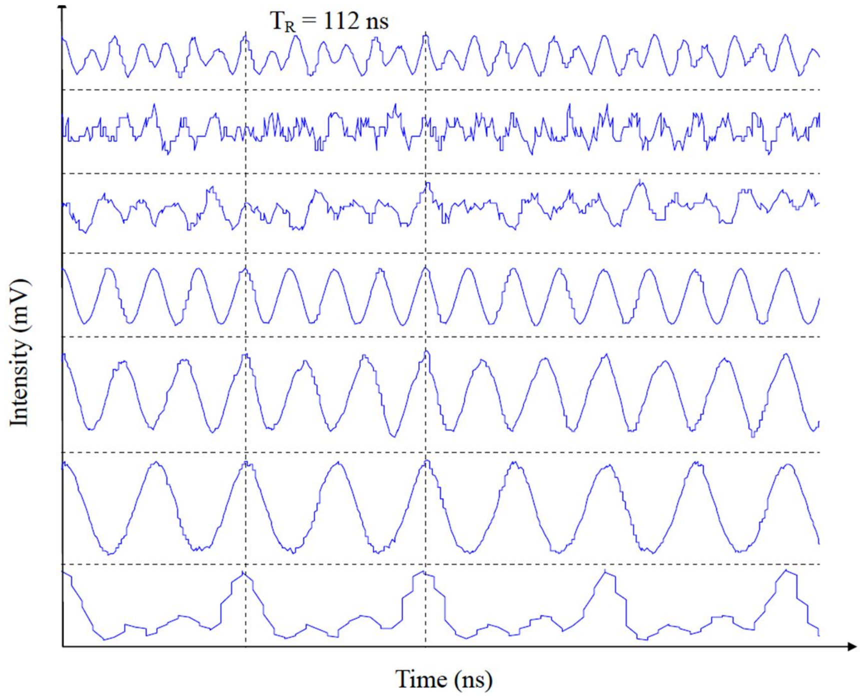

FIG. 3. Self-locking observations in the output of 11.3 m, Er-doped ZBLAN fiber laser with a concentration of 80000 ppm molar. The self locking occurred at different harmonics of the round trip cavity time T_R, ranging between 1-1/7.

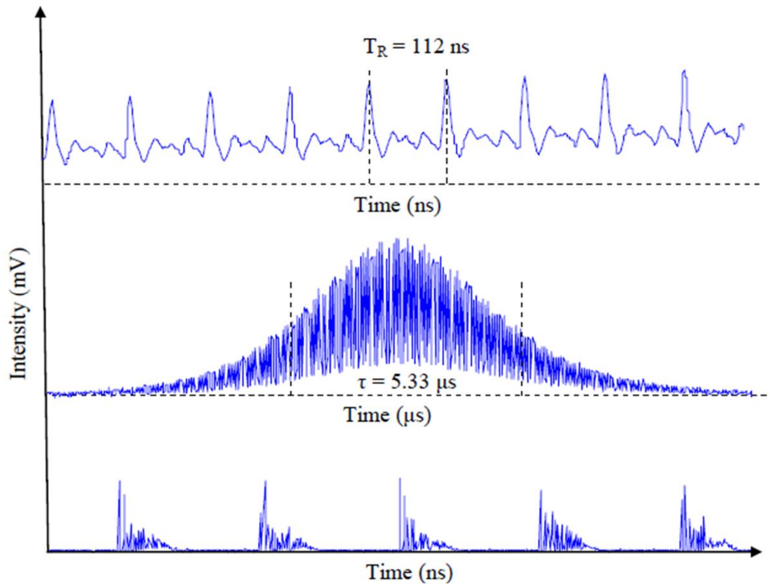

FIG. 4. Observations of self-locking in the output of 11.3 m, Er-doped ZBLAN fiber laser when pulse pumped by a modulated input, 1ms on and 1ms off, from 970 nm diode laser. The peak power of the high intensity laser pulse was 2.1W.

Observations of Harmonic-Locking in Single-Clad Ho, Pr-Doped ZBLAN Fiber Lasers

Fig. 5 shows the experimental arrangement for this study.

The fiber was pumped by a single mode vertically polarised Nd: YAG laser operating at 1064 nm. An objective lens with a NA of 0.25 was used to launch the pump laser light reflected from a 45º dichroic mirror into the fiber. The mirror was 99 % HR at the pump wavelength and 97% HT with an antireflection coating at the lasing wavelength. The end facet of the fiber was butted against a HR mirror at both the pump and lasing wavelengths, so that the cavity consisted of Fresnel reflection and a highly reflecting mirror. Cut-back measurements were carried out in which the launch and the slope efficiencies and optimum length of the fiber were determined. It was found that approximately 85% of the incident power could be launched into the fiber resulted in more than 600 mW output power at a slope efficiency of ~ 9% for the near optimum length of the fiber laser of 9.2 m. The detection of the output was carried out using an InGaAs photodiode.

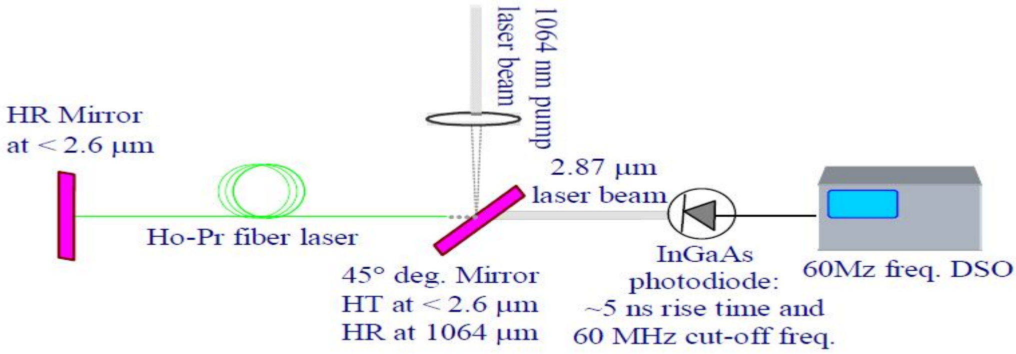

FIG. 5. Experimental arrangement for Ho, Pr-doped ZBLAN fiber laser pumped by a Nd: YAG laser.

The temporal profiles of the output for several lengths of the fiber: 8.84 m, 9.2 m, 9.75 m, 10.6 m and 13.25 m were investigated. The output consisted of a train of short pulses with a time interval which fluctuated between T_R and 1/3 T_R for fiber lengths > 9.2 m and fixed at the around cavity round trip time for 8.8m, as shown in Fig. 6.

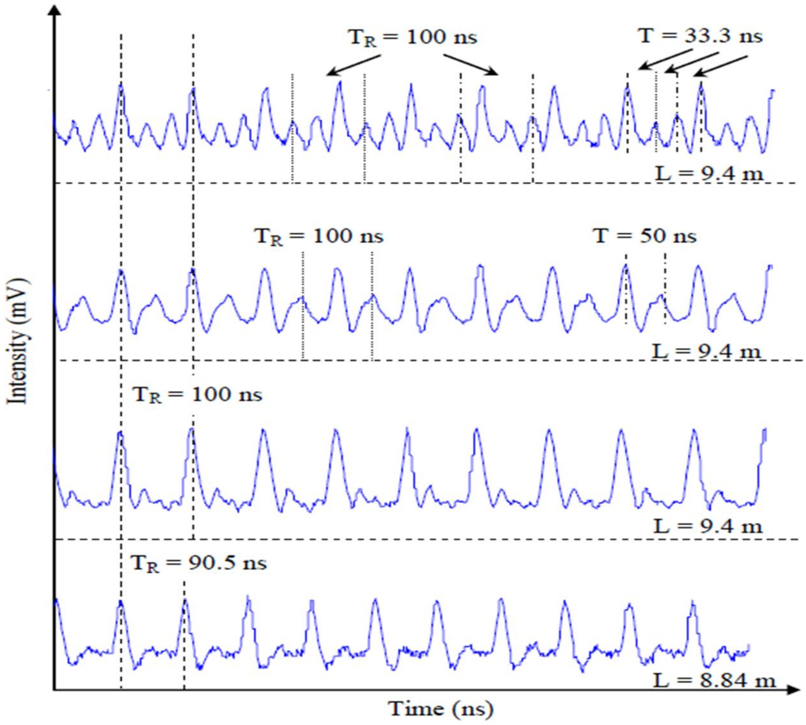

FIG. 6. Observation of self-locking in the output of Ho, Pr-doped ZBLAN fiber laser. For a fiber length of 9.4 m the self-locking was unstable and the period between the pulses varied between 1-1/3 T_R (cavity round trip time). For shorter fiber length 8.84 m the self-mode-locking time was fixed at the cavity round trip time T_R.

Similar to the observations on the Er fiber no effect was found on the strength of the pump power on the temporal behaviour of the fiber; the train of short pulses was observed for all powers down to the threshold, as shown in Fig. 7.

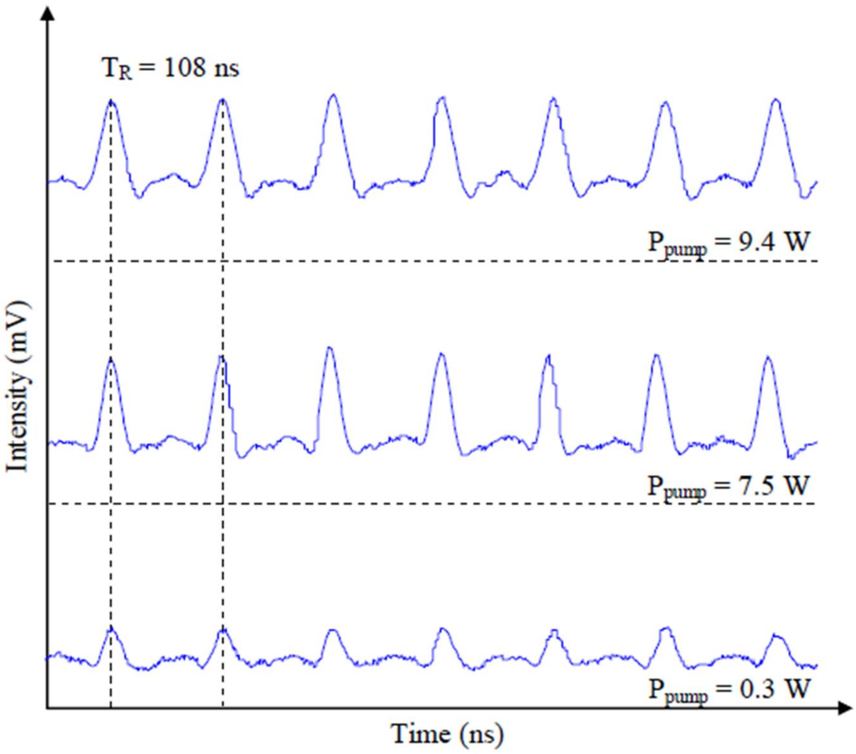

FIG. 7. Self-locking observations in the output of the Ho, Pr-doped ZBLAN fiber laser at various pump powers for a fiber of length 10.6 m. The period between the pulses varied between 1-1/3 T_R (cavity round trip time); for the purpose of comparison the train of pulses that locked at the time equal to the cavity round trip is shown in this figure.

The period between the two main pulses was measured for several lengths of the fiber and matched the round trip cavity time which can be calculated from T = 2nl/c, where n is the refractive index of the fiber, L the length of the cavity and c is the velocity of light. Fig. 8 shows a perfect match between the experimental results and theoretical values for the single-clad Ho^{3+}, Pr^{3+}-doped ZBLAN fiber laser considering n ~ 1.52 for this fiber.

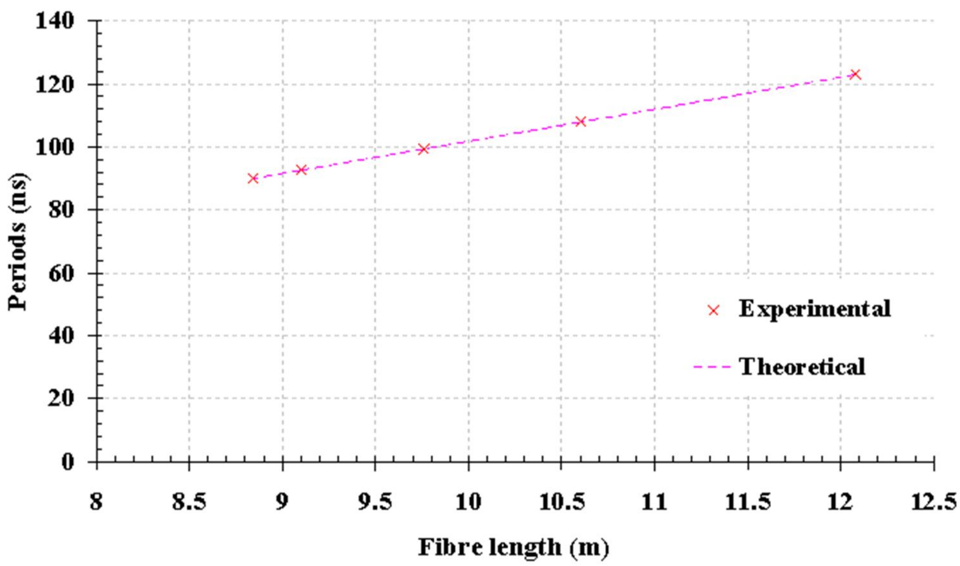

FIG. 8. Comparison between the experimental results and theoretical values of the self-locking at cavity round trip time, observed in the output of Ho, Pr-doped ZBLAN fiber laser.

Discussions

The experimental observations showed that the output of the heavily fluoride fiber laser emitting near 3 µm consisted of a train of short pulses. For true mode-locking the period between two main pulses should match the round trip cavity time, TR =2nl/c, where n is the refractive index of the fiber, l is the length of the cavity and c is the velocity of light. Fig. 8 shows a perfect match between the experimental and theoretical values for the single-clad Ho, Pr-doped ZBLAN fiber laser assuming n~1.52 for this fiber. The same match has also been found between the experimental results (75 ns and 113ns) and theoretical values (74.6ns, 112.8 ns) for the 50000 and 80000 ppm double-clad Er-doped ZBLAN fibers considering the fiber refractive index n~1.47. The harmonics of the theoretical values match the harmonics of the experimental results. This suggests that the fiber is self-locked at the harmonics of the round trip cavity. This self-locked output was accompanied by CW emission which indicated that not all the longitudinal modes are locked, and this may be because the fiber is a high gain medium and very strong locking should apply. Also from the previous observations it was demonstrated experimentally that the key elements required to generate stable and perhaps full CW modelocking with 100 % modulation depth are the length of the fiber as well as the dopant concentration. According to our previous studies [12, 13] the origin of the mode-locking effect in heavily doped fiber lasers may be considered to be due to the following mechanisms:

a) The un-pumped far end of the fiber re-absorber the laser beam and thus act as internal passive saturable absorber. The modulation depth and recovery time of this passive saturable absorber increases with the length of the fiber. For a very long fiber, the modulation by saturable absorber becomes strong enough to lock some of the longitudinal modes on a time scale shorter than the round trip cavity [18 -25].
b) The frequency pulling contribution for the heavily doped material is strong enough to lock some of the longitudinal modes to match the round trip cavity time, and possibly for the more heavily doped fiber as was seen for the Er-doped ZBLAN fiber. This frequency becomes large enough to lock some of the modes on a time scale shorter than the round trip cavity time. Also the interactions between ions in the heavily doped fiber at certain dopant levels become larger, as the ion-ion distance is smaller. This leads to huge fluctuations in the self-locking of the output, i.e. continuous changing of the locked pulse repetition frequency.
c) Another possible explanation is that the self-locking is due to the Stark levels within the $^{13}I_2$ and $^{5}I_7$ energy levels in Er- and Ho, Pr-doped fluoride fiber lasers [31]. The self-locking is considered to result from ion-pair interaction, leading to fast movement between the Stark levels in the lower lasing energy level of the $^{13}I_2$ in Er and $^{5}I_7$ in Ho, and thus acting like a fast saturable absorber. The ion-pair interaction increases with the longer fiber as the affective area of the saturable absorber increases for the longer fiber length, resulting in stronger absorption effects and thus stronger modulation. This interaction can be increased by increasing the concentration of the dopant material. Strong ion-pair interaction between the Stark levels can lead to a very fast recovery time and strong modulation in the laser cavity, which in turn can be responsible for locking the modes in a time shorter than the cavity round trip.

Conclusion

The temporal profiles of the output of an Er-ZBLAN fiber operating at ~2.7 µm and a Ho, Pr-ZBLAN fiber operating at ~2.87 µm have been investigated. The temporal profile of the output of these fiber lasers is found to be self mode-locked. The self mode-locking was stable for short fibers or for low concentration. For the Er-doped ZBLAN fiber the output was locked at half the round trip cavity time for a fiber with concentration of 50000 ppm, or at harmonics of the round trip cavity time for a fiber of 80000 ppm, with interpulse periods up to 1/7 T_R. The output from the Ho, Pr-doped ZBLAN was locked at the cavity round trip time for a fiber of 8.8 m length, while locked at harmonics of this time for longer fibers. The length and concentration of the doped material has a major effect on the repetition rate and stability of the self mode-locking in these fibers, while no dependence found on the pump strength in the self-locking behaviour. The origin of the harmonic self mode-locking in heavily doped 3µm fiber lasers is attributed to the existence of saturable absorption in the fiber core, frequency pulling contribution for the doped material or ion-pair interactions leading to fast movement between the Stark levels in the lower lasing energy levels.

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