774
Cambridge 93

EXTERNALLY INITIATED PASSIVE MODE-LOCKING IN FIBRE LASER

I.Yu.Khrushchev, A.B.Grudinin* and E.M.Dianov
General Physics Institute
38 Vavilov str., 117942, Moscow, Russia
* - *now with Optoelectronics Research Centre*
Southampton, S09 5NH, U.K.

Introduction.

Passively mode - locked fibre Soliton Lasers (PSL) have recently become of considerable interest owing to their ability to produce ultrashort pulses in a simple laser cavity configuration. In addition, a lot of interesting effects are involved in the PSL operation. The mode-locking process in PSL is similar to that of a laser with a fast saturable absorber and is initiated by the most intensive fluctuation of the intracavity energy flow [1]. Another important feature of PSL is the soliton nature of the generated pulses resulting in a well-defined energy of an individual pulse [2]. Typically, PSL generates a few pulses per round-trip period, and the time interval between pulses is a random value as there is no force holding pulses at certain time distance. Nevertheless, under certain circumstancies, the laser output pattern demonstrates stability during several minutes [3].

Thus, the study of the possibility to initiate mode-locking process by a regular external signal and to generate sequences of pulses predetermined by this signal is of considerable importance.

Experiment.

The process of external initiation of the mode-locked regime of PSL has been studied with the Figure-8 laser whose operation is based on the reflection properties of the nonlinear loop mirror (NALM) [4].

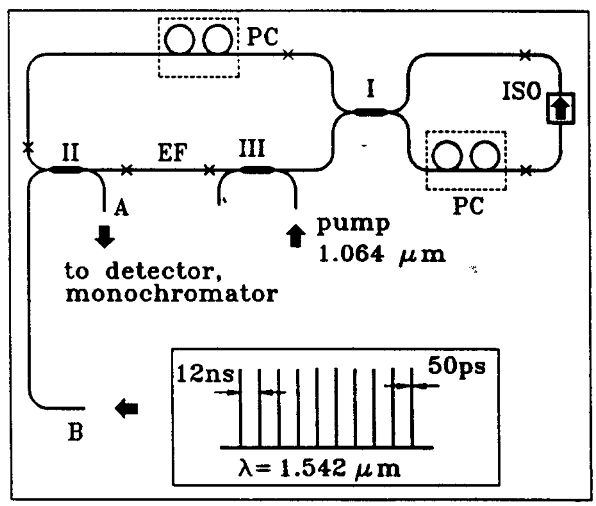

Fig.1. Experimental setup. PC - polarization controllers; ISO - isolators; EF - active fibre. Inset shows an oscilloscope trace of the seeding signal.

The experimental configuration employed a loop coupler arranged to give 50:50 coupling at 1560 nm. The unidirectional loop consists of a polarization dependent isolator, a 5 m length of a single-mode fibre and polarization control discs (PCs). The total NALM length was 50 m and the fundamental ring frequency was 3 MHz. Fibre dispersion $D = -4$ ps/nm·km at 1560 nm. The amplifier section consists of a 4m fibre codoped with Yr and Er ions, their concentration being 5000 ppm and 800 ppm respectively. Pump power was launched through a wavelength division multiplexer (WDM) II with zero output coupling at 1560 nm, while WDM III (90 % output coupling at 1560 nm) was used for launching an external signal through port A, and output signal was taken at port B.

As a source of the external signal we used cascade stimulated Raman scattering in an auxiliary fibre excited by a Q-switched and mode-locked Nd:YAG laser (λ =1064 nm) resulting in generation of Raman solitons in 1500-1600 nm wavelength region [5]. After spectral filtration the radiation was launched into the laser cavity, so we were able to inject a signal of approximately constant peak power at different wavelengths. Since the signal laser was operating in mode-locked and Q-switched modes simultaneously, in the time domain the injected signal showed up as a sequence of 10 pulses with 13 ns time separation (Q-switched envelope). There were ~20 Raman solitons under each 100 ps envelope (i.e. mode-locked pulse). So each time we injected into the cavity approximately 200 ultra-short pulses with estimated peak power of 10 W inside the cavity. This source of the external signal may operate either with frequency of 1 kHz or in manual reqime. The later mode of operation has been used in all the experiments with this PSL.

Results and discussion.

To begin with, the laser was arranged for self-started mode-locking by the proper positioning of polarization controllers. The pump power corresponded to the second threshold P_2 (point of mode-locking selfstart). Under this conditions the laser output spectra were measured. The interesting feature of the laser was that wavelengths of generation in cw and mode-locked regimes did not coincide being equal to 1535 nm and 1543 nm respectively.

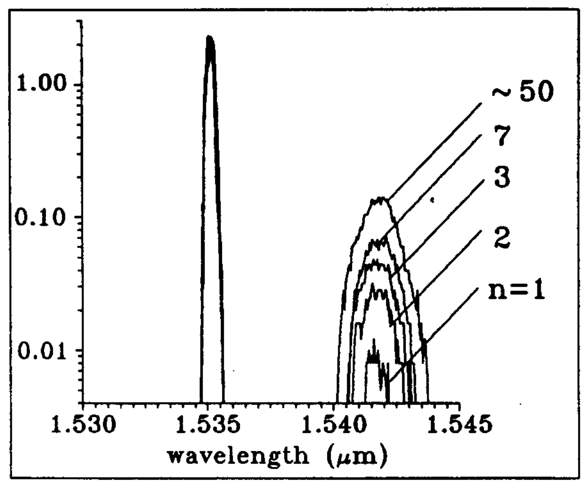

Fig.2. Spectra of the laser output when *n* pulses in the cavity are generated.

The next step of the study was the measurement of the peak power of the external signal required for initiation of mode-locking process. The laser was operating in cw reqime and an external signal was launched into the cavity at different pump power levels below P_2. Central wavelength of the injected signal was 1543 nm. We have found out that the external signal initiated mode-locking when the pump power was in the range of $0.5P_2 < P < P_2$ and the peak power of the injected signal was about 1 W (i.e. equaled by the order of magnitude the peak power of the fundamental soliton travelling within the cavity). This relatively high value can be explained if one takes into consideration the dispersion broadening of the seeding 200 fs pulse in nonlinear loop. This broadening results in low contrast of the seeding pulse switching in the NALM. Another possible explanation is an arbitrary polarization state of the seeding signal.

The required peak power can be slightly reduced (by about 20%) if the pump power is increased up to $P \sim P_2$. Below $P \simeq 0.5P_2$ mode-locking process did not start at any level of peak power of the injected signal up to 10 W.

Despite the very broad gain bandwidth of erbium fibre amplifiers (~ 30nm) the spectral bandwidth of ultra-short pulses produced by PSL is much narrower being normally equal to 2-10 nm centering at the wavelength of the gain-loss equilibrium. Therefore it was interesting to clear up how spectral and temporal characteristics of the injected signal affect the output characteristics of the PSL. For this purpose we examined the self-starting abilities of the PSL initiated by a signal at different central wavelengths. PSL pump power was $0.8P_2$. As expected, the laser run into the mode-locked regime if wavelength of the injected signal lay within the spectral bandwidth of steady-state mode-locked pulses. The laser output characteristics were the same when it the laser self-started from the noise level (i.e. truly self-started laser) or with initiation of mode-locking process by 200 fs pulses. The laser output has never reproduced the regular sequence of the injected pulses.

Effect of energy quantization in the PSL [2] results in existence of many pulses within the laser cavity and the number of pulses is defined by the pump power. This, in principle, permits to exploit such type of lasers as an optical memory. To investigate this possibility, we pumped the laser nearly the second threshold keeping it operating in cw regime, and launched an external signal centered at 1542 nm. By adjusting the level of the seed we were able to initiate exactly one mode-locked pulse after injection a single train of 10 pulses. The Fig.2 shows output spectra of the laser for different numbers of travelling pulses. Fig.3 represents corresponding oscillograms. Note that the relative position of individual pulses was very stable and invariable during tens of minutes and we did not observe any time jitter despite the fact that after ten minutes of travelling two adjacent pulses cover a distance of more than 100 million of kilometers.

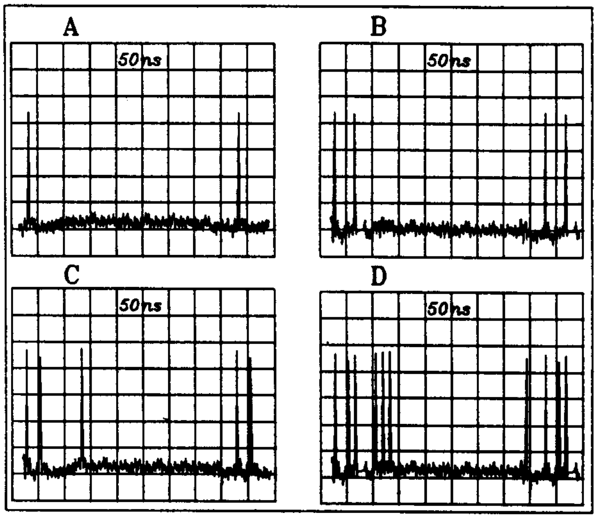

Fig.3. Oscillscope traces of the fibre laser output. A) - one pulse injected; B) - two pulses; C) -three pulses and D) - seven pulses.

When the number of pulses had reached ~30, then each new injected signal resulted in change of the time interval between pulses without increasing the number of existing pulses.

Conclusion.

We have presented for the first time experimental results on initiation of passive mode-locking by an external signal. The results show that keeping the laser pump power below the second threshold and using an appropriate external source, it is possible to achieve stable single- or multi-pulse generation. As a source of the external signal in the experiments we have used a

YAG laser and an auxiliary fibre. However the mode-locking process can be initiated by any signal with a suitable wavelength and peak power. From this point of view, a source of the external signal based on a laser diode and a fibre amlifier appears to be more promising.

Regarding the possibility to exploite such configuration as an optical memory, it is still unclear if the laser can "remember" the relative distance between pulses or, like the characteristics of an individual pulse, a pulse train is in some way defined by the laser parameters. This question will be answred shortly.

References

[1] Kryukov P.G. and Letokhov V.S., 1972 *IEEE J. Quantum. Electron.* **8** 766.
[2] Grudinin A.B., Richardson D.J. and Payne D.N., 1992 *Electron. Lett.* **28** 67.
[3] Khrushchev I.Yu., Grudinin A.B., Dianov E.M., 1992 *VIII Conf. on Ultrafast Phenomena*, MC25.
[4] Bulushev A.G., Dianov E.M. and Okhotnikov O.G., 1991 *Opt. Lett.* **16** 88.
[5] Dianov E.M., Grudinin A.B., Khaidarov D.V., Korobkin D.V., Prokhorov A.M. and Serkin V.N., 1989 *Fiber and Intergrated Optics* **8** 61.