Topological engineering of mode-locked fibre lasers: NALM/NALM2 technologies

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Topological engineering of mode-locked fibre lasers: NALM/NALM2 technologies

A.V.Ivanenko[a], A.Y.Kokhanovskiy[a], M.D.Gervaziev[a], S.V.Smirnov[a],
S.K.Kobtsev[a], S.K.Turitsyn[a,b]
[a]Novosibirsk State University, Pirogova 2, Novosibirsk, 630090
[b]Aston Institute of Photonic Technologies, Aston University, B4 7ET, Birmingham, UK

ABSTRACT

The work presents for the first time a comparative study of mode-locked figure-8 laser, in which two independently pumped active media are located either in the same or in different cavity loops. It is shown that the NALM2 configuration (both active media in the same cavity loop) delivers both higher average and peak radiation power. Flexibility of NALM/NALM2 technologies is further demonstrated for implementation of algorithmic electronically driven control over radiation mode-locking regimes. Also discussed are the results of experimental testing of electronic methods relying on NALM/NALM2 technologies for setting desired generation regimes.

Keywords: mode-locked fibre laser, nonlinear amplifying loop mirror, topological engineering.

1. INTRODUCTION

Passive mode locking in fibre lasers with an artificial saturable absorber provides record-setting energy parameters of generated pulses, as far as both the pulse energy [1] and the radiation average power [2] are concerned. As opposed to real ultrafast saturable absorbers, the artificial saturable absorbers are spectrally universal, as a rule, they feature femtosecond-level response time, and withstand substantially higher pulse energy and average power, while ensuring intensity-dependent transmission. An important advantage of artificial saturable absorbers is adjustability of their parameters, which can also be implemented electronically. Artificial saturable absorbers based on nonlinear amplifying loop mirrors (NALM) are successfully used in a great number of laser systems and their productive application prompts further advancement of laser systems relying on NALM. One of the important developments of NALM technology was addition of a second independently pumped active medium into the laser cavity with NALM. Introduction of a second active medium directly into the NALM loop [3, 4] gave rise to the NALM2 technology, whereas a second active medium added to the initially passive loop of an F8 fibre laser [5, 6] transformed its cavity into a double NALM (we will henceforward term it D-NALM). The location of specific elements along the fibre laser cavity [7] and its general topology affect the laser generation properties. Topological engineering of mode-locked fibre lasers is an important problem, whose solution requires detailed studies of laser cavities with different topologies.

This work offers for the first time a comparative study of generation properties of a passively mode-locked figure-8 laser, where two independently pumped active media are located either in the same cavity loop or in different ones.

2. EXPERIMENT

The studied laser cavities are schematically shown in Fig. 1: the NALM2 configuration in Fig. 1a and the D-NALM one in Fig. 1b. In order to minimise the effect of nonlinear polarisation evolution, both cavities only included fibres and other components that maintained the radiation polarisation. Two ytterbium-doped 2.5-m long fibres with absorption of 3.9 dB/m at 978 nm were used as active media. Both these fibres maintained polarisation and had double cladding. They were pumped through fibre beam combiners with independent multi-mode laser diodes emitting around 978 nm. Each laser diode could deliver 5.5 W of output.

To ensure uni-directional generation, an optical isolator was inserted into one of the cavity loops. For coupling the radiation out of the cavity, a 30/70 fibre coupler was included into the same loop. An extra 3.3-m long stretch of passive fibre was spliced into the other loop .

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To comprehensively measure the parameters of observed pulsed generation regimes, we used an automated system for measurement of auto-correlation function (APE pulseCheck 120 fs ... 150 ps), RF inter-mode beat signal (Tektronix RSA 3308B with 2-Hz resolution), and optical spectrum (Yokogawa AQ 6375 with resolution 0.02 nm).

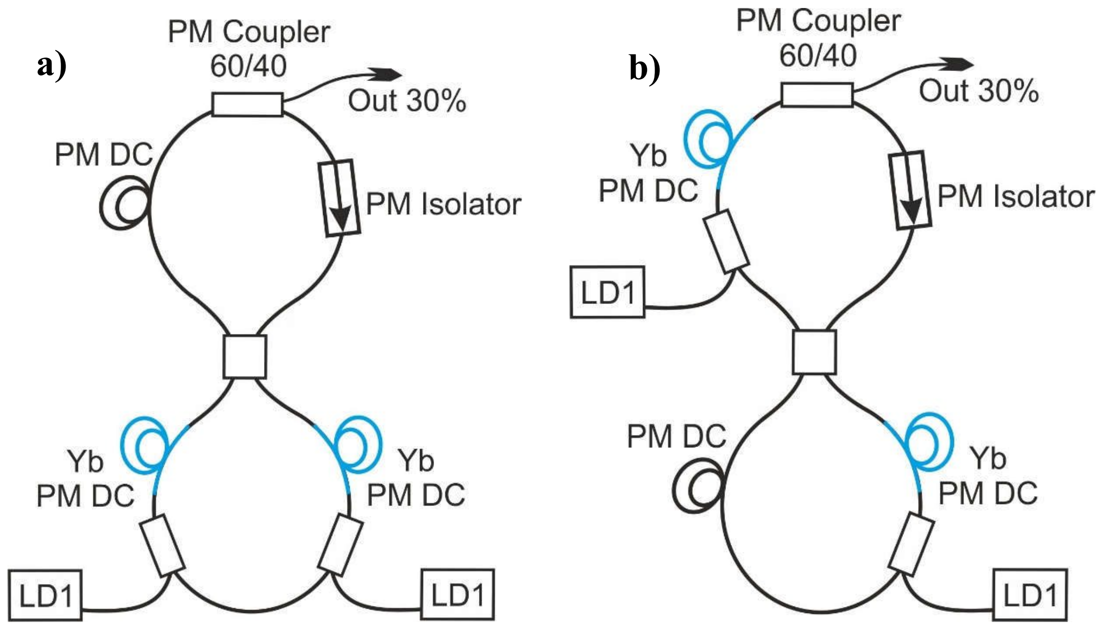

Figure 1: Layouts of laser cavities with two active media: a) NALM2 cavity, b) D-NALM cavity. LD1, 2 – laser diode pump, Comb – WDM fibre beam combiner, Yb PM DC – polarisation-maintaining active ytterbium-doped fibre with double cladding, Coupler – radiation out-coupler..

3. RESULTS AND DISCUSSION

Both studied systems exhibited a plethora of generation regimes depending on the ratio and the absolute output power of the two active media. It was possible to trigger generation of single pulses (over the cavity round trip), including double-scale pulses [8, 9], as well as multi-pulsed generation. The shape and spectral width of the pulsed radiation also varied in relatively broad limits. In order to systematise the great variety of generated data, we created maps for dependencies of generated pulse parameters upon the ratio and absolute power level of the pump radiation expressed in injection current values for both pump laser diodes.

In Fig. 2, maps for distribution of contrast of RF inter-mode beat signal are given. It can be generally observed that the best inter-mode beat contrast corresponding to the most stable mode locking operation is reached around the highest pump power level of one of the two active media

A similar distribution is also seen for the duration of the auto-correlation function of the generated pulses (Fig. 3).

Fig. 4 presents distributions of single-scale and double-scale pulse generation. Quite obviously, the area corresponding to existence of both single- and double-scale pulse generation is noticeably larger for the D-NALM laser configuration.

The commonality of the two studied systems consisted in observation of four typical generation regimes where stable mode locking was observed depending on the ratio and absolute power of the pump radiation sources. The parameters of these regimes are listed in the following Fig. 5 and 6.

Fig. 7 gives a distribution map of output pulse peak power and auto-correlation functions for pulses with the highest peak power. As it can be concluded from Fig. 5, the NALM2 configuration allows generation of higher peak powers of the output pulses. In experiments with the D-NALM laser configuration, a generation regime was observed with single-scale pulses and the highest average output power of 170 mW. In contrast, the laser with NALM2 layout in the regime generating single-scale pulses delivered the average output power as high as 380 mW. The higher pulse peak power in the NALM2 configuration is corroborated by high efficiency of second harmonic generation obtained from the auto-correlator (Fig. 7. ACF).

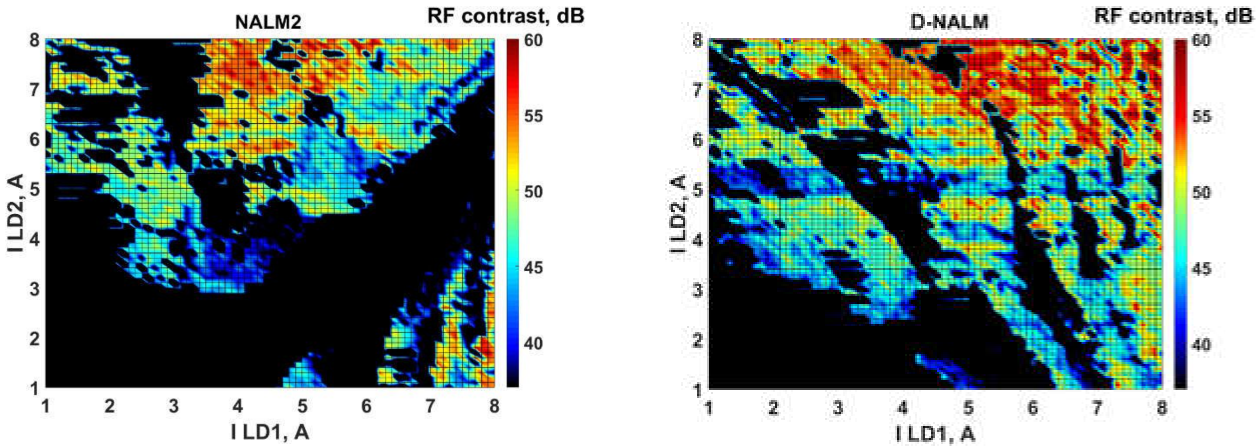

Figure 2. Maps of distribution of RF inter-mode beat spectrum in the two studied configurations of the laser cavity: a) NALM2 laser, б) D-NALM laser.

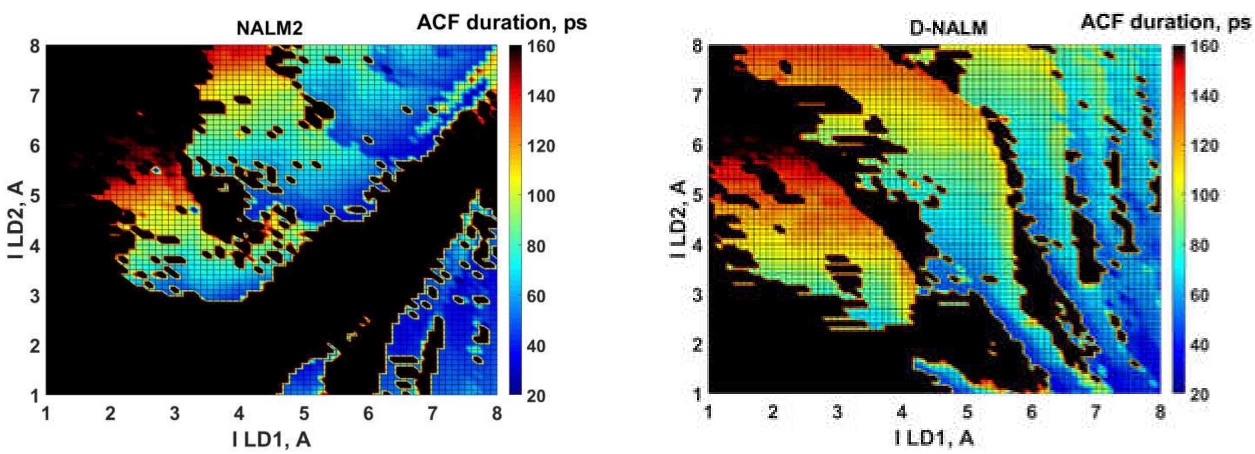

Figure 3. Distribution maps of the auto-correlation function of the generated pulses in the two studied laser configurations: a) NALM2 laser, б) D-NALM laser.

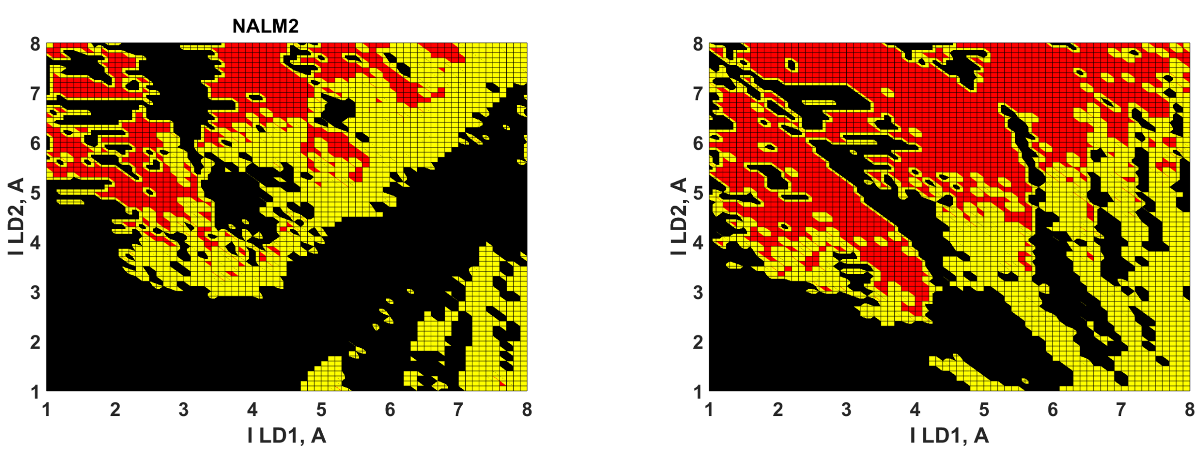

Figure 4. Distribution of generation regimes with single-scale pulses (red), double-scale pulses (yellow), and no pulses (black) in the studied cavity configurations: a) NALM2 cavity, б) D-NALM cavity.

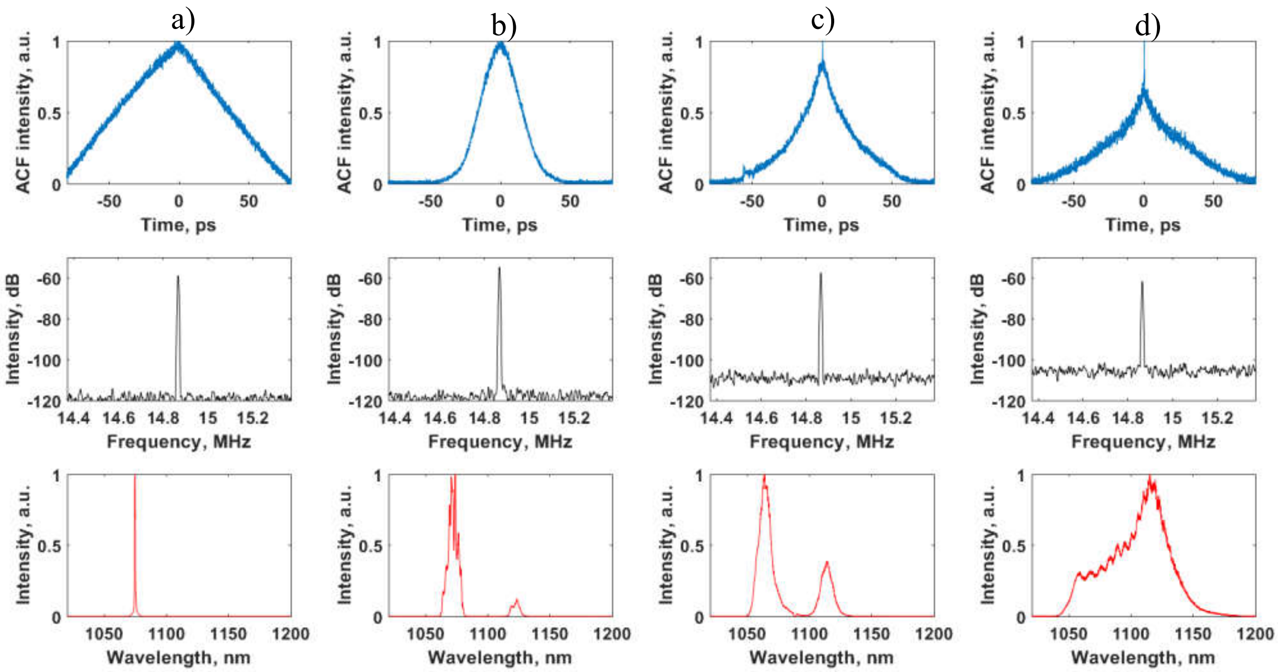

Figure 5. a) Single-scale pulses of long duration with narrow radiation spectrum, b) Single-scale pulses of short duration with broad radiation spectrum, c) Double-scale pulses of long duration with broad radiation spectrum, d) Double-scale pulses of long duration with ultra-broad radiation spectrum.

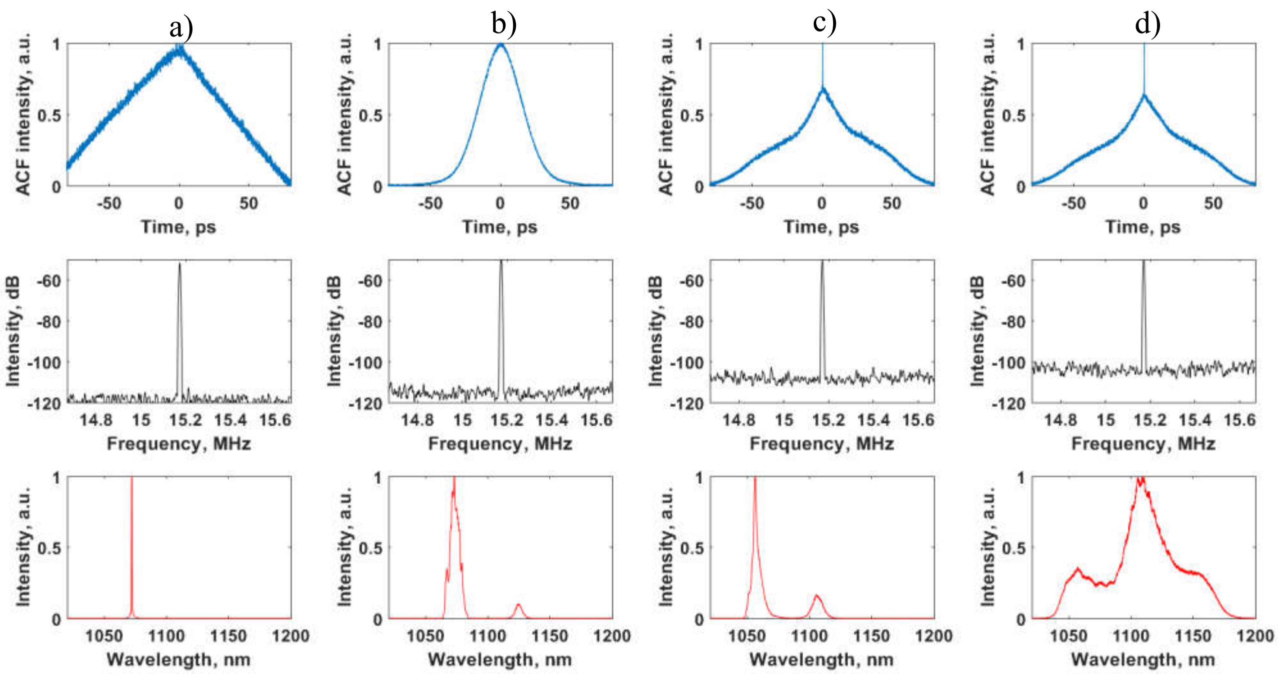

Figure 6. a) Single-scale pulses of long duration with narrow radiation spectrum, b) Single-scale pulses of short duration with broad radiation spectrum, c) Double-scale pulses of long duration with broad radiation spectrum, d) Double-scale pulses of long duration with ultra-broad radiation spectrum.

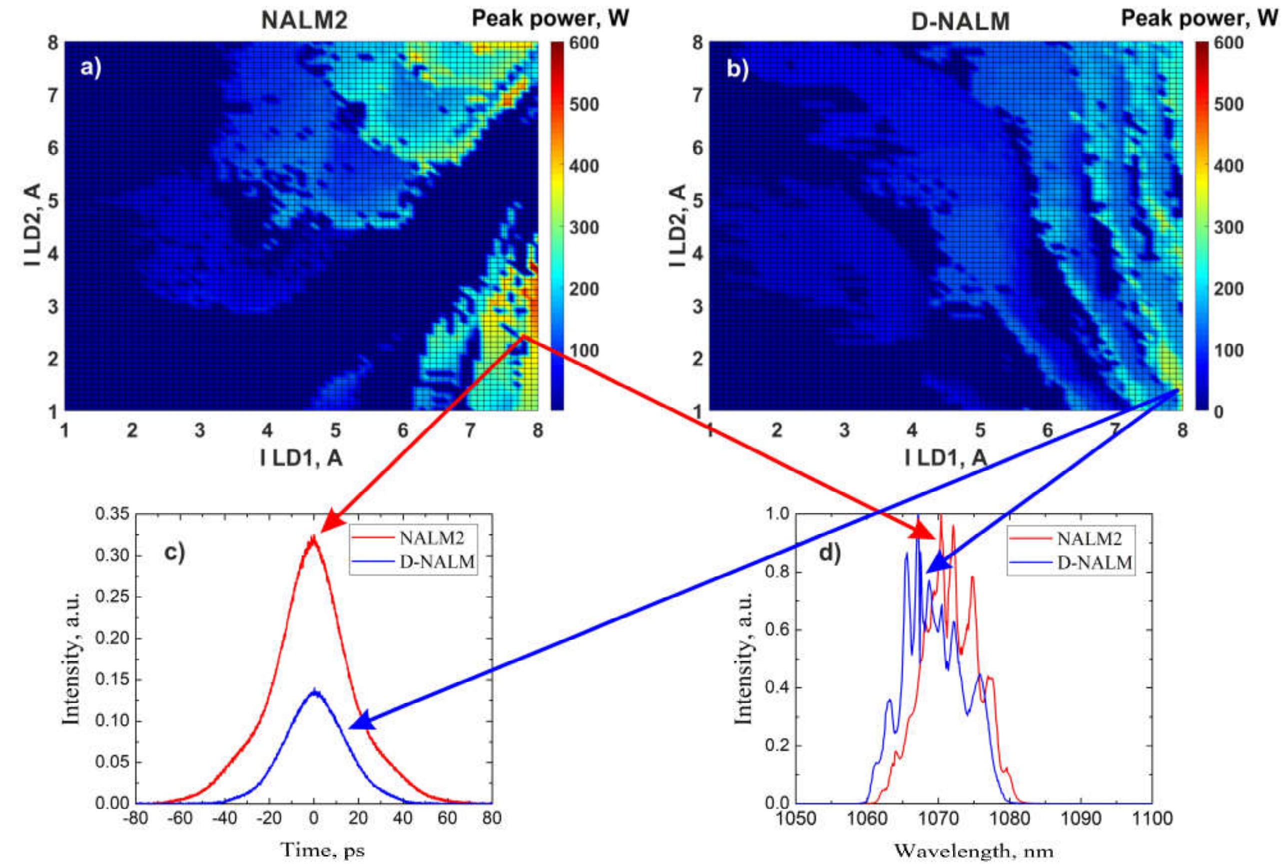

Figure 7. Distribution maps of output pulse peak powers, as well as optical spectra and auto-correlation functions measured for pulses with the highest observed peak power for the two studied cavity configurations: a) NALM2 cavity, б) D-NALM cavity.

CONCLUSION

This work for the first time presents the results of a comparative experimental analysis of a passively mode-locked fibre laser with different cavity topologies. Two configurations of F8 cavities with two active media were studied. In one of them, both active media were located in the same cavity loop (NALM2 technology), whereas in the other, they were placed in different loops (D-NALN technology). Both configurations demonstrated a rich variety of generation regimes depending on the ratio and the absolute level of the radiation power of the two sources each pumping one of the active media. During the conducted experiments, we measured distribution maps of RF inter-mode beat spectra, duration of the pulse auto-correlation functions, and peak radiation power of the generated pulses. It was shown that the NALM2 configuration delivers significantly higher (more than twice as high) output pulse peak power. Pulse parameters corresponding to four characteristic generation regimes were reported. The obtained results open the prospect of development of highly efficient smart laser systems based on NALM2 technology.

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