Self-Tuning Short-Pulse Fibre Lasers with Automated Algorithmic Optimisation

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Abstract: We report self-optimising fibre lasers that achieve on-demand autonomous spectral tuning and variable short-pulse generation by passive birefringent filtering, governed by genetic algorithms and electronic control of the cavity transfer function.

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1. Introduction

Fibre lasers can exhibit a range of temporal and spectral output properties through harnessing both linear and nonlinear filtering effects in the cavity. Nonlinear polarisation rotation (NPR), for example, is commonly exploited for pulse generation in combination with a polariser to form an intensity-dependent filter: i.e. an artificial saturable absorber (SA). Despite advances in new *real* SA materials [1], *artificial* SA technologies remain attractive for their simple implementation and quasi-instantaneous response time. Their usage outside research environments has been limited however, by a need for careful cavity optimisation (through polarisation and power control) to ensure a strong SA response (where optimal properties vary with the environment due to fibre birefringence fluctuations). Additional opportunities exist for exploiting linear birefringent filtering to tune laser operating wavelengths, without the need for free-space filters, although similar limitations exist [2]. Therefore, an expert user is typically required to operate and optimise passive polarisation-based filtering in fibre lasers.

A solution to this problem is to employ advances in artificial intelligence to develop systems capable of learning how to complete advanced tasks, such as harnessing complex, coupled fibre-optic effects in a laser cavity to achieve a given output [3]. Within this domain, genetic algorithms (GAs) were recently demonstrated for optimisation of mode-locking [4, 5], building on earlier demonstrations of semi-automated laser tuning using simpler algorithms [6]. Here, we extend the concept of GA-controlled filtering to achieve automated spectral tuning in addition to pulsation (by Q-switching and mode-locking), and discuss the practicalities of this approach.

2. Automated Laser Design and Performance

We have considered all-fibre ring cavities including both NPR and nonlinear amplifying loop mirror (NALM) SAs to confirm the broad applicability of this approach to numerous laser designs. An example cavity is shown in Fig. 1a, including 4 electronically controllable quarter waveplates (QWP) and a computer-controlled pump diode. We developed a GA which applies evolutionary biological principles to evolve a set of 5 system parameters (i.e. 4 QWP angles and pump power) towards optimal performance (i.e. desired laser behaviour), as determined by a fitness function. The GA starts with a population of random parameters (“generation 1”) and scores the performance of each by electronically setting the QWPs and pump diode, then measuring the output. Subsequent generations are formed through selective breeding of the best parameters to obtain new, improved combinations.

2.1. *Wavelength Tuning*

To demonstrate self-tuning by exploiting linear birefringent filtering, a fitness function F is defined to assign a higher score for measured laser wavelengths λ that are closer to a user-specified target λ_0: $F_\lambda = 1 - \frac{|\lambda - \lambda_0|}{30\ \text{nm}}$ An example evolution process with $\lambda_0 = 1550$ nm is shown in Fig. 1(b-c): the initial generation yields a random selection of wavelengths, and through breeding of the best system parameters, the GA locates the target wavelength and converges towards it after several iterations. We repeated the experiment with target wavelengths within the amplifier bandwidth, achieving automated tuning across the 1542–1600 nm range (to 0.1 nm accuracy).

2.2. *Tunable Q-Switching*

We extend consideration to the temporal domain in order to optimise the nonlinear birefringent filtering for pulse generation by Q-switching. The duration and repetition rate of Q-switched pulses depend on the SA response, thus

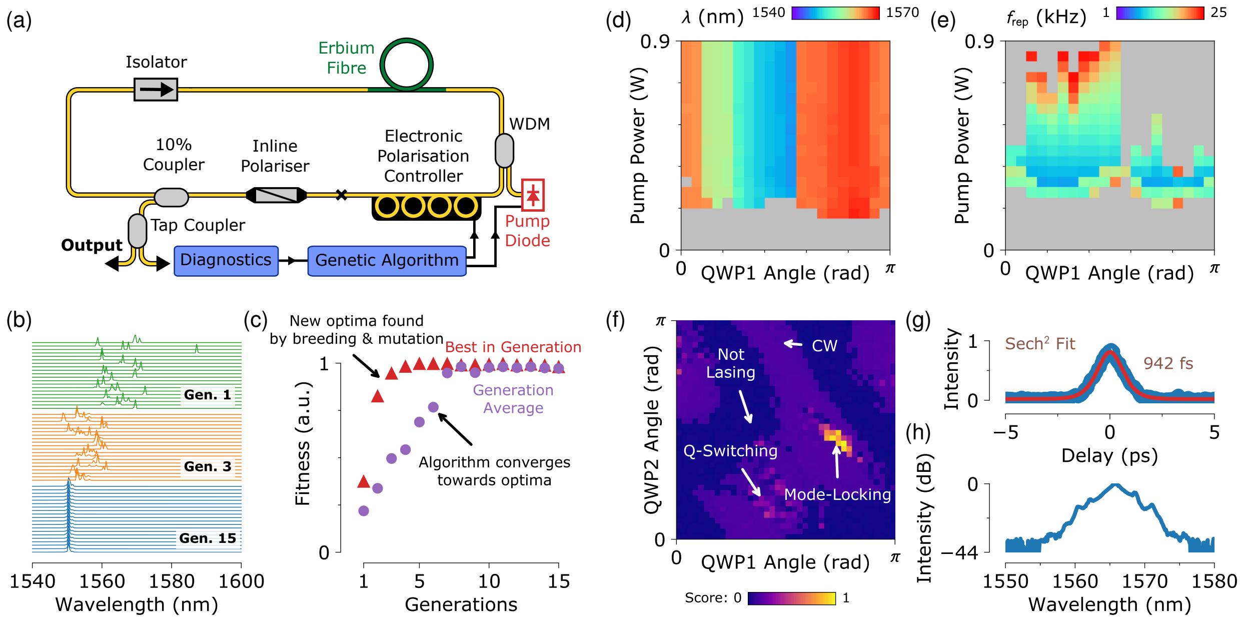

Fig. 1. (a) Cavity schematic; (b)–(c) Self-tuning spectral evolution; (d) wavelength and (e) Q-switched repetition rate variation with 2 parameters varying (other 3 fixed); (f) variation of fitness in 2D parameter space, showing small mode-locking regime: (g) autocorrelation and (h) spectrum.

suggesting tunability of pulse properties through control of QWP & pump power parameters. To highlight the rich diversity of possible output states, we systematically sweep the pump from 0 to 0.9 W and one QWP angle through π radians, while measuring the output spectrum and oscilloscope trace. This is a small two-dimensional (2D) slice of the system's 5D parameter space, yet shows a wide range of laser properties can be accessed including Q-switched pulse operation with repetition rates from 1 to 25 kHz (Fig. 1(d-e)). By adjusting the fitness function to score pulse outputs of a given repetition rate highly, we were able to demonstrate autonomous self-tuning of the laser to any desired repetition rate in this range.

2.3. Mode-Locking

Through careful adjustment of the artificial SA response by varying the QWP angles and pump power, it it possible to generate ultrashort pulses by phase-locking of cavity modes. We define a fitness function to highly score a fundamentally mode-locked output (targeting a broad optical spectrum and high signal-to-noise ratio for harmonics measured on an RF spectrum analyser) [5], with lower scores assigned for Q-switched pulses and CW lasing. The small region of stable mode-locking is seen in another 2D slice of parameter space (Fig. 1f), which can be repeatably and reliably located using the GA, to obtain self-starting mode-locking, even in the presence of intentional environment variation, generating 942 fs pulses (Fig. 1(g-h)). For the fastest convergence speed, we found that different GA parameters are required for achieving mode-locking and self-tuning Q-switching [7].

3. Conclusion

We have demonstrated automated tuning of both spectral and temporal laser properties using a genetic algorithm to harness passive birefringent filtering. This approach paves to way to fully automated 'smart' photonic systems.

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