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On Cascaded Raman Amplifier Control*

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Abstract—Extremum Seeking Control is applied to the control of cascaded Raman amplifiers for long-haul wavelength division multiplexed optical communications systems. Simulation demonstrates the effectiveness of this control strategy.

I. INTRODUCTION

Raman amplifiers are finding widespread use in submarine DWDM systems and in terrestrial long haul systems when improved optical signal to noise ratio is required and when amplifier spacings are greater than are suitable for erbium doped fibre amplifiers [1], [2]. Current static systems are evolving into dynamic systems with the introduction of reconfigurable optical add drop multiplexers and the promise of the longer term vision of all optical networks. However, such dynamic networks add new complexity to the closed loop control of optical amplifiers in the presence of transients, resulting in the need for new approaches to amplifier transient control that address both long and short timescale performance requirements. Whilst many amplifier control strategies presented in the literature are concerned with short timescale transient control (see for example [3], [4]), few papers examine the long timescale transient control problem.

In this paper, an approach to this long timescale transient control problem is presented. In particular, an extremum seeking control (ESC) algorithm developed and documented in [5] is applied to a simulation setup comprising of four pumps and forty signal channels, where the objectives are to (i) minimize output signal power ripple, and (ii) minimize the deviation of the output signal power from a desired level. The results presented indicate that the ESC algorithm of [5] is indeed effective in achieving this objective.

II. RAMAN AMPLIFIER OPERATION

Physical setup: The Raman amplifier considered here operates on an optical fibre link that consists of the following components, systems and signals:

- 1) A *distributed* optical fibre span $\mathcal{S}^-$ of length L^- .
- 2) A *discrete* optical fibre span $\mathcal{S}^+$ of length L^+ .
- 3) $n_p = n_p^- + n_p^+$ pump lasers (actuators) with individual power control inputs given by the elements of the vector $u^\mp$, centered at a set of discrete wavelengths $\Lambda^{p\mp} = \{\lambda_i^{p\mp} | i = 1, 2, \dots, n_p^\mp\}$.
- 4) $n_s^\mp$ optical coupling devices, collectively denoted $B^\mp$, to launch the various pump wavelengths into the fibre spans at particular locations.

- 5) n_s exogenously generated and applied signals (data), each with an individual power given by the elements of the vector d , centered at a set of discrete wavelengths $\Lambda^s = \{\lambda_i^s | i = 1, 2, \dots, n_s\}$.
- 6) $n_s^\mp$ optical coupling devices and sensors, collectively denoted by $H^\mp$ to measure the propagating signal power vectors $y^\mp$, indexed by signal wavelength, at two locations along the fibre.

The components and systems listed above can be assembled into the Raman amplifier setup $\mathcal{L}$ shown in Figure 1, which consists of a distributed *backward pumped* amplifier $\mathcal{L}^-$ and a discrete *forward pumped* amplifier $\mathcal{L}^+$ in cascade. In this setup, signal photons are injected via d by some external network or device, and propagate downstream (from left to right), before leaving the amplifier via y . Pump photons, on the other hand, can propagate upstream or downstream depending on whether they are injected by u^- or u^+ , or from elsewhere in the optical network via v^- or v^+ .

Power dynamics across a fibre span: Modelling the complete dynamics of a Raman amplifier requires an application of the nonlinear Schrödinger equation, a simpler average field power model [2] suffices for Raman amplifier fibre spans. This model is described by the first order nonlinear vector PDE

$$\tau \frac{\partial \mathbf{P}}{\partial t} + \mu \frac{\partial \mathbf{P}}{\partial z} = -A\mathbf{P} + \text{diag}(\mathbf{P})C\mathbf{P} \quad (1)$$

where $\mathbf{P} \equiv \mathbf{P}(t, z)$ is the augmented vector of backward propagating pump powers $\mathbf{P}^{p-}$, forward propagating pump powers $\mathbf{P}^{p+}$, and forward propagating signal power $\mathbf{P}^s$, all at time t and distance z from the upstream end of the span. There, τ , μ , A represent respectively matrices of propagation delays per unit length, propagation directions, losses per unit length, and coupling coefficients per unit length. τ , μ and A are diagonal matrices, with the i^{th} diagonal entry corresponding to the wavelength of the i^{th} entry in $\mathbf{P}$. The units of τ and A are respectively $\mu s (km)^{-1}$, and $(km)^{-1}$. Matrix μ is dimensionless, with $\mu_{ii} = -1$ for backward propagating wavelengths and $\mu_{ii} = 1$ for forward propagating wavelengths. C_{ij} denotes the coupling coefficient from the j^{th} to the i^{th} wavelength of $\mathbf{P}$.

Raman amplifiers and cascades: [5] The fibre span model (1) is a fundamental building block that can be used in the construction of models for a variety of Raman amplifier configurations and cascades. Figure 1 illustrates the amplifier configuration of interest here. In particular, the amplifier $\mathcal{L}$ shown consists of a distributed backward pumped amplifier

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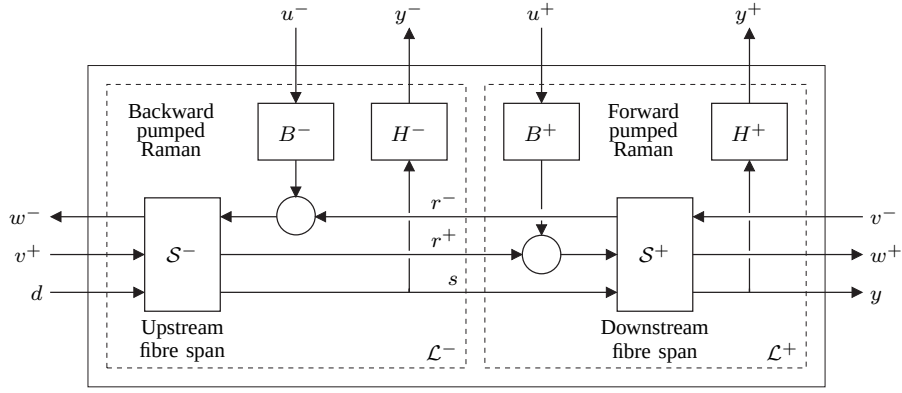


Fig. 1. A forward and backward pumped Raman amplifier cascade.

$\mathcal{L}^-$ whose output is connected to the input of a discrete forward pumped amplifier $\mathcal{L}^+$. These component amplifiers utilize, respectively, a span $\mathcal{S}^-$ of length L^- with input / output operators B^- and H^- , and a span $\mathcal{S}^+$ of length L^+ with input / output operators B^+ and H^+ , as shown in Figure 1. Models of cascades of cascades, as shown in Figure 2, can be constructed in an analogous fashion. Consequently, such systems can ultimately be considered as cascaded instances of the fibre span model (1), which together can be modelled in terms of *flows* and *output maps*, as required in the general framework of [6].

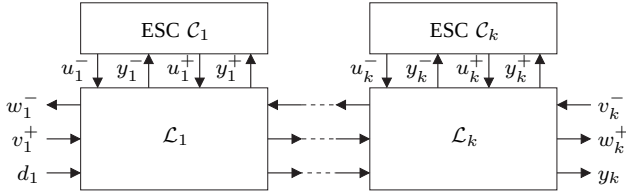


Fig. 2. An optical link consisting of cascaded Raman amplifiers.

III. EXTREMUM SEEKING

Background: Extremum seeking control (ESC) is a paradigm whose principal aim is finding an extremum of an unknown reference-to-output steady state map. While ESC is quite old, its rigorous stability analysis was only recently addressed and established. Indeed, local stability properties of a class of extremum seeking algorithms were proved for the first time in [7] and, more recently, non-local stability was shown under stronger conditions in [8]. Stability of a very different type of ESC that is more related to the classical nonlinear optimization and nonlinear programming methods was presented in [6]. This ESC was shown to yield stability with extremum seeking under very weak conditions allowing, for instance, non-smooth reference-to-output maps, infinite dimensional attractors for the system dynamics and multiple control inputs. The results in [6] provide a theoretical framework for the ESC design here.

Theoretical basis: [6] Consider a system (for example, a Raman amplifier) that is representable by a flow $\mathcal{F}$ and an output map $h : X \rightarrow \mathbf{R}^p$, so that a trajectory of the system state and output and output are given respectively by

$\phi \in \mathcal{F}(\xi, \theta)$ and $h(\phi)$, where $\xi \in X$ is the initial system state in the Banach space X , and $\theta \in \mathbf{R}^p$ is the parameter (or input value) that selects a particular trajectory (or subset of trajectories). Let $J : \mathbf{R}^p \rightarrow \mathbf{R}$ denote a “cost” function, selected by the user, that quantifies some trajectory-based measure of performance of the system that is to be optimized. Suppose that for any fixed parameter value θ , the state of the system converges to an output uniquely determined by that particular input and that this results in a convergence of the function $J(h(\cdot, \xi, \theta))$ to a constant value, uniquely determined by the fixed parameter θ . Then, the following input-to-output map, called a “readout map”, is well defined:

$$g(\theta) := \lim_{t \rightarrow \infty} J(h(\phi(t, \xi, \theta))). \quad (2)$$

In addition, suppose that the map g defines a non-empty set of minimizers (or maximizers) of g . Then, under some additional technical assumptions [6], there exists a controller, mapping measurements $h(\cdot, \xi, \theta)$ to parameters θ that approximately minimizes (or maximizes) the readout map g in real time. Furthermore, this controller can be obtained by following the ESC design steps [6], [5]:

- 1) Modelling, including cost function selection;
- 2) Optimization algorithm selection or design;
- 3) Algorithm approximation;
- 4) ESC algorithm implementation.

Application to Raman amplifier control: The control topology of interest in Raman amplifier control is shown in Figure 2. The control objective is to flatten the downstream signal power spectrum, whilst regulating that signal power such that the amplifier has unity overall gain. This is to be achieved via the feedback of the downstream signal power measurement y^+ (here, $H^- \equiv 0$, eliminating y^-) through a controller $\mathcal{C}$ to the pump power inputs u^- and u^+ . $\mathcal{C}$ is to utilize the ESC algorithm obtainable using the design framework outlined above. Following that framework, the amplifier or cascade is modelled in 1) in terms of fibre spans, inputs and outputs, as described previously. The cost function selected to achieve the control objective is

$$J(h) = (h - h^*)' Q (h - h^*) + \sum_{i,j=1, i \neq j}^{n_s} \left(\frac{h_i - h_j}{\lambda_i^s - \lambda_j^s} \right)^2.$$

Here, Q is some square, positive semi-definite matrix, and h^* is the desired downstream signal power as measurable via $H^+ = I$ (the identity operator). The optimization algorithm in 2) is selected off-the-shelf (steepest descent). This algorithm is capable of optimizing the static mapping defined by the cost function J composed with the output map $h \equiv H^+$ and flow (based on (1)) used to model the amplifiers. In 3), this algorithm is modified for real time implementation, requiring the approximation of quantities such as gradients in terms of the available measurements y^+ . Furthermore, as all measurements must be separated according to [6] by a fixed waiting time T , this waiting time must be approximated. This can be done based on the settling time T_s of the linearized dynamics of the underlying flow, or of the non-depleted pump approximation. Selecting $T \gg T_s$ is then sufficient. Finally, the algorithm of 2) approximated in 3) must be implemented in hardware or simulation to implement the ESC $\mathcal{C}$.

Simulations: The specifications of the backward and forward pumped amplifiers $\mathcal{L}^-$ and $\mathcal{L}^+$ defining $\mathcal{L}$ in Figure 1 are based on representative values [2], [1], [9], [10], [11]. Four pumps ($n_p^- = 2$, $n_p^+ = 2$) and forty signals are considered. The lengths of the fibre spans used are selected arbitrarily to be $L^- = L^+ = 50 \text{ km}$. An upstream signal power of -10 dBm per channel is assumed. The spectrum used is based on that of [3].

An ESC algorithm is then implemented, as per the preceding section, in closed loop with a finite difference PDE solver that models the two fibre spans, couplers and sensors. The resulting simulated steady state pump and signal power spectra before and after application of ESC are shown in Figures 3, 4 and 5. There, the signal power ripple and set-point tracking error at the downstream end of the discrete downstream fibre span have been reduced to $< 1 \text{ dB}$. It is also of interest to note that the ESC algorithm drops the third pump in this situation (each pump has a designated minimum output power of -20 dBm).

IV. CONCLUSION

In this paper, the ESC algorithm developed in [5] was applied to a simulation of a four pump, forty signal cascaded Raman amplifier system. Two control objectives were pursued, namely, flat signal spectrum and output signal power regulation. A signal power ripple of $< 1 \text{ dB}$ was achieved, with deviation of $< 1 \text{ dB}$ from the desired output power level. This was found to be consistent with experimental setups documented in the literature (see for example [3]).

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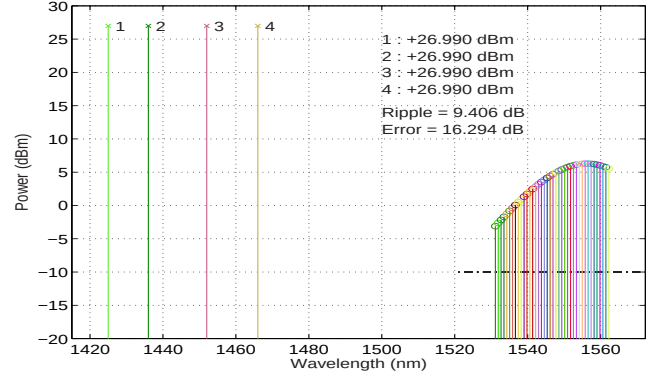


Fig. 3. Spectrum prior to ESC implementation.

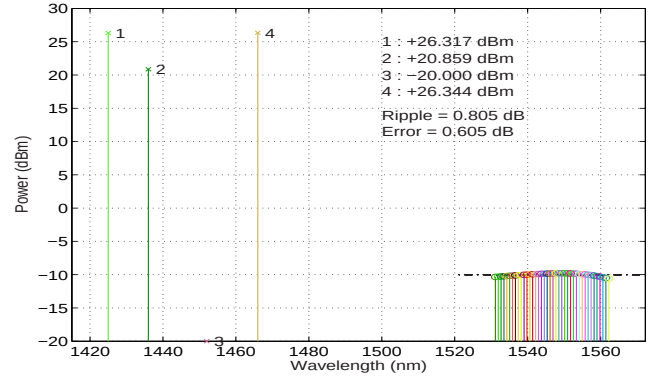


Fig. 4. Spectrum after ESC implementation.

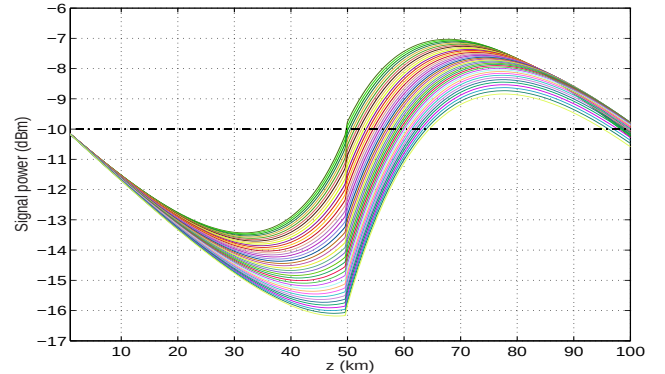


Fig. 5. Spatial power distribution after ESC implementation.

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