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Laser pulse shaping via extremum seeking ☆

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ABSTRACT

Extremum seeking, a non-model based optimization scheme, is employed to design laser pulse shapes that maximize the amount of stored energy extracted from the amplifier gain medium for a fixed input energy and inversion density. For this pulse shaping problem, a double-pass laser amplifier whose dynamics are fully coupled and composed of two nonlinear, first-order hyperbolic partial differential equations, with time delays in the boundary conditions, and a nonlinear ordinary differential equation, is considered. These complex dynamics make the optimization problem difficult, if not impossible, to solve analytically and make the application of non-model based optimization techniques necessary. Hence, the laser pulse shaping problem is formulated as a finite-time optimal control problem, which is solved by first, parameterizing the input pulse and pumping rate over the system's finite time interval and then, utilizing extremum seeking to maximize the associated cost function. The advantage of the approach is that the model information is not required for optimization. The extremum seeking methodology reveals that a rather non-obvious laser pumping rate waveform increases the laser gain by inducing a resonant response in the laser's nonlinear dynamics. Numerical simulations illustrate the effectiveness of the approach proposed in the paper.

1. Introduction

Background and motivation: Maximizing the energy extracted by a laser pulse is critical in many laser applications. In the polysilicon process for manufacturing flat panel displays, one of the outstanding problems is obtaining enough instantaneous laser power to melt as large an area as desired (e.g., one continuous melt of several meters along the substrate for a flat panel TV display). One engineering solution is to use several laser amplifiers and combine their outputs, but using a single amplifier more efficiently is preferable. The energy efficiency is also a growing concern in photolithography, where a drive to increase scanner wafer-per-hour throughout means that the optical exposures (which have a fixed energy dose required to print an image, set by the chemistry of the photoresist) must be accomplished with fewer pulses of higher energy. The goal in this paper is to optimize laser pulse shapes to maximize the amount of stored energy extracted from the amplifier gain medium for a fixed input energy and inversion density.

In Frantz and Nodvik (1963), the growth of a radiation pulse in a laser amplifier was described by nonlinear, time-dependent photon transport equations, which account for the effect of the radiation on the medium as well as vice versa. In Akashi, Sakai, and Tagashira (1995), a one-dimensional model including Poisson's equation to consider the space-charge for a discharge-excited ArF excimer laser has been developed. In the recent work (Ren, Frihauf, Krstić, & Rafac, 2011), a single-pass laser model is described by a coupled nonlinear first-order hyperbolic partial differential equation (PDE) and a nonlinear ordinary differential equation (ODE). This model is extended from the classical model (Frantz & Nodvik, 1963). In this paper, a double-pass laser model is considered with partial overlap and optical feedback in the amplifier, which adds another PDE and time delays in the boundary conditions. This setup allows for more efficient energy extraction and a longer output pulse length.

Design tool—extremum seeking: For two coupled first-order PDEs, with nonlinear coupling of Lotka–Volterra type, boundary control was developed in Pavel and Chang (2009) to drive the state at the end of the spatial domain to the desired constant reference values. Instead of stabilization, the laser pulse shape optimization problem is addressed in this paper. However, the complex dynamics in the laser amplifier model makes the optimization problem difficult, if not impossible, to solve analytically and make the application of non-model based optimization techniques necessary. The extremum seeking method (Ariyur & Krstić, 2003) is employed to design the finite-time optimal input signal and pumping rate to maximize the amount of stored

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energy extracted from the amplifier gain medium for a fixed input energy and inversion density.

Extremum seeking is a real-time, non-model based optimization approach for dynamic problems where the system is assumed to have a potentially nonlinear equilibrium map with local minima or maxima, but is otherwise unknown. This method performs optimization by estimating the gradient of a cost function and driving this gradient to zero. The gradient estimation is performed using perturbation signals that are typically deterministic periodic signals, e.g., sinusoids (Ariyur & Krstić, 2003), but can be replaced by stochastic excitation signals (Liu & Krstić, 2010; Manzie & Krstić, 2009), or existing disturbances affecting the system (Carnevale et al., 2009). A popular tool in control applications in the 1940–1950s, extremum seeking has seen a resurgence after its stability analysis was established in Krstić and Wang (2000) for continuous-time systems and in Choi, Krstić, Ariyur, and Lee (2002) for discrete-time systems. Many successful applications of extremum seeking have been reported in the literature, including particle beam matching (Schuster et al., 2007), flow control (Becker, King, Petz, & Nitsche, 2007), tokamak fusion devices (Ou et al., 2008), source seeking with nonholonomic unicycles (Cochran, Kanso, Kelly, Xiong, & Krstić, 2009; Zhang, Arnold, Ghods, Siranosian, & Krstić, 2007), control of combustion instability (Banaszuk, Ariyur, Krstić, & Jacobson, 2004), maximizing the pressure rise in an axial flow compressor (Wang, Yeung, & Krstić, 2000), limit cycle minimization (Wang & Krstić, 2000), optimal positioning of mobile sensors under stochastic noise (Stanković & Stipanović, 2010), control of thermoacoustic instability (Moase, Manzie, & Brear, 2010), and optical fibre amplifiers (Dower, Farrell, & Nesić, 2008). However, extremum seeking has never before been used in high-performance photolithography light source systems.

Results: Motivated by Frihauf, Krstić, and Başar (2011), where extremum seeking was introduced to solve noncooperative games with infinitely-many players, the laser pulse shaping problem is formulated as a finite-time optimal control problem, by parameterizing the evolution of the input pulse and pumping rate in the time interval [0,T], and employing extremum seeking to maximize the associated cost function. Both a Gaussian input pulse shape parameterization and a general input pulse shape parameterization that consists of a summation of weighted finite characteristic functions are considered. The advantage of the approach is that modeling information of the laser amplifier is not required in the pulse shaping optimization via extremum seeking, and the effectiveness of this approach is shown through numerous simulations. Though the optimal pulse shape may not converge to the same shape for different initial conditions, the amplifier gain does improve for each case. In general, it is difficult to achieve global optimization using extremum seeking when multiple extrema exist (Tan, Nesic, Mareels, & Astolfi, 2009), which is expected for the high-dimensional extremum seeking problem considered in this paper. A rather non-obvious laser pumping rate waveform, which increases the laser gain by inducing a resonant response in the laser's nonlinear dynamics, is obtained using the extremum seeking approach.

Organization: The optimization problem is formulated in Section 2 and solved using extremum seeking for a Gaussian input peak timing

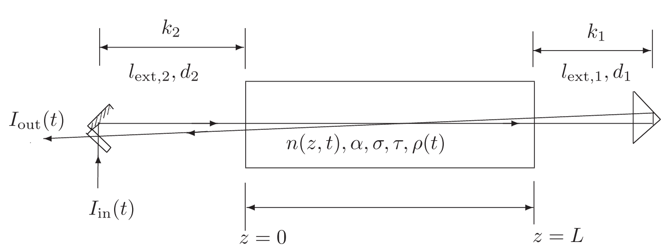

Fig. 1. Double-pass laser amplifier with partial overlap and optical feedback.

optimization in Section 3 and a general input pulse shape optimization in Section 4. In Section 5, both the input pulse and the pumping rate are optimized simultaneously. Throughout this work, the effectiveness of the proposed method is demonstrated by extensive numerical studies. Finally, some concluding remarks are given in Section 6.

2. Double-pass laser dynamics with partial overlap and optical feedback

The intensity dynamics of the laser beam in Fig. 1 are described as follows for $z \in (0,L], t \geq 0$:

$$\begin{cases} \dfrac{\partial I_{\text{lr}}(z,t)}{\partial t} = -c\dfrac{\partial I_{\text{lr}}(z,t)}{\partial z} + \sigma c n(z,t) I_{\text{lr}}(x,t) \\ \qquad -\alpha I_{\text{lr}}(z,t), \\ \dfrac{\partial I_{\text{rl}}(z,t)}{\partial t} = c\dfrac{\partial I_{\text{rl}}(z,t)}{\partial z} + \sigma c n(z,t) I_{\text{rl}}(z,t) \\ \qquad -\alpha I_{\text{rl}}(z,t), \\ \dfrac{\partial n(z,t)}{\partial t} = -\dfrac{1}{F_{\text{sat}}}[I_{\text{lr}}(z,t)+I_{\text{rl}}(z,t)]n(z,t) \\ \qquad -\dfrac{1}{\tau}n(z,t)+\rho(t), \end{cases} \tag{1}$$

with boundary conditions

$$\begin{cases} I_{\text{lr}}(0,t) = k_2 I_{\text{rl}}(0,t-2d_2)+(1-k_2)I_{\text{in}}(t-d_2), \\ \qquad \text{boundary condition/input}, \\ I_{\text{rl}}(L,t) = k_1 I_{\text{lr}}(L,t-2d_1), \\ \qquad \text{boundary condition}, \\ I_{\text{out}}(t) = (1-k_2)I_{\text{rl}}(0,t-d_2)+k_2 I_{\text{in}}(t), \\ \qquad \text{boundary value/output}, \end{cases} \tag{2}$$

where I_{lr} and I_{rl} are the rightward and leftward irradiance, respectively, n is the population difference between the upper and lower laser levels, and ρ is the pumping rate, k_1 and k_2 are partial overlap and optical feedback gains, $l_{\text{ext},1}$ and $l_{\text{ext},2}$ are the right and left extended lengths, and $d_1 = l_{\text{ext},1}/c$ and $d_2 = l_{\text{ext},2}/c$ are time delays caused by the extended lengths. The physical meanings and values of the parameters are listed in Table 1.

The objective is to seek the optimal input pulse shape $I_{\text{in}}(t)$ over the time interval $t \in [0,T]$ such that the amplifier gain

$$\mathcal{G} = \frac{E_{\text{out}}}{E_{\text{in}}}, \tag{3}$$

Table 1
Parameters of the laser system.

Parameter	Description	Value (units)
L	Length of gain medium	0.5 (m)
T	Evolution duration time of laser dynamics	300 (ns)
c	Speed of light	3×10^8 (m/s)
σ	Stimulated emission cross section	2.8×10^{-16} (cm^2)
α	Distributed loss	0.006 (cm^{-1})
τ	Lifetime of laser state	1.75 (ns)
F_{sat}	Saturation fluence	3.67 (mJ/cm^2)
k_1	Partial overlap gain	0.85
k_2	Optical feedback gain	0.95
$l_{\text{ext},1}$	Extended length (right)	0.7 (m)
$l_{\text{ext},2}$	Extended length (left)	0.8 (m)
d_1	Time delay (right)	2.3 (ns)
d_2	Time delay (left)	2.7 (ns)
E_{in}	Input energy	Fixed
E_{out}	Output energy	To be optimized
V_ρ	Inversion density	Fixed
$\mathcal{G} = \frac{E_{\text{out}}}{E_{\text{in}}}$	Amplifier gain	To be optimized