Controlling Actively Q-switched Laser Output by Nonlinear State Feedback

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Q-switched lasers are prevalent in applications that require high intensity laser in ultra short pulses. For many medical applications of Q-switched lasers, it is crucial to have smooth and controlled pulse shapes [1, 2]. In dermatological applications, for instance, an irregular shape or duration of a laser pulse during pigmentation removal can cause serious damage to the surrounding healthy tissues [2]. In optical communication applications it is essential to produce reliable and clean pulse shapes. Q-switched fiber lasers are ideal candidates for optical signal generations for optical communication since light is already coupled into the fiber. However when fiber lasers are Q-switched, one often obtains complicated pulse shapes with multiple peaks. Thus, precise regulation of the output pulse shape would be a truly enabling technology for the application of fiber lasers in optical communications.

In this paper the powerful nonlinear control methodology known as *feedback linearization* is applied in order to enhance the performance of Q-switched lasers. Feedback linearization, which is a common technique routinely used in control engineering, is virtually unknown in the field of photonics. But it appears to be directly applicable. Specifically, the authors describe an actively Q-switched laser system where the desired output pulse shape is generated by nonlinear feedback control. A typical Q-switched laser system operates as follows. For a certain duration of time, the losses in the cavity are kept high enough to prevent the laser oscillation threshold from being reached. Therefore, a large population inversion is built up by the continued pumping. When the losses are suddenly lowered, a rapidly rising intense laser pulse develops because of the large amplification for stimulated emission. Thus, the whole population inversion that has been built up is quickly depleted, and consequently, a high intensity laser pulse with a very short duration is produced. Switching the cavity losses is equivalent to switching the quality factor, Q, of the cavity. Thus, such a laser is called Q-switched. In a solid state laser Q-switching regime, the laser rate equations are a set of nonlinear coupled differential equations involving the photon flux, $\phi(t)$, and the average inversion density, $n(t)$, as follows:

$$d\phi/dt = \phi\,(c\sigma nl/L - \varepsilon(t)\,/t_r), \quad 1(a)$$

$$dn/dt = R_p - \gamma_g n - \gamma n\phi\sigma c, \quad 1(b)$$

[3], and the laser output power, P_{out}, is $\phi h\nu$. Here the authors take into account the pump rate, R_p, and the contribution from spontaneous emission, $\gamma_g n$, which are omitted in [3]. The key to the Q-switch is the dissipation loss function, $\varepsilon(t)$, which represents the output coupling losses and the losses introduced by the Q-switch. Typically, the loss function $\varepsilon(t)$ is modulated in an acousto-optic modulator where an acoustic signal is used to modulate the diffraction loss of the Q-switch.

Using established methods from the field of geometric nonlinear control, a feedback control law is designed to produce the exact modulating acoustic signal needed to generate the desired output. The control law requires knowledge of the instantaneous values of the photon flux, $\phi(t)$, and the average population inversion density, $n(t)$. Estimates of the photon flux can be obtained by measuring the laser output. The average population inversion density can be estimated by monitoring the florescence [4]. In the context of control engineering, the governing laser rate equations 1(a) - (b) of the Q-switched laser can be viewed as a second order nonlinear *state space system* with the state variables, $\phi(t)$ and $n(t)$. The loss function, $\varepsilon(t)$, and the laser power output, P_{out}, are considered as the input and the output functions of the nonlinear state space model, respectively. Feedback linearization control technique is particularly suited for a nonlinear state space realization with a well-defined *relative degree,* ***r*** [5]. This refers to the number of times the output function needs to be differentiated in order for the input function to appear explicitly. It is easily shown that the Q-switched laser system has a relative degree of one. In the case that the relative degree is strictly less than the number of states, **n**, the closed loop system has **n-r** hidden modes, the so-called zero dynamics, that need to be at least locally stable in order for the design to be feasible. It will be shown for the Q-switched laser system that these zero dynamics are globally asymptotically stable. This prototype design is validated by Simulation using MATLAB *Simulink* software. Robustness issues will also be addressed by simulation and through the method of sliding mode control [6].

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