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An application of L_2 nonlinear control and gain scheduling to erbium doped fiber amplifiers

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Abstract

This paper presents an application of control theory towards suppressing cross-gain modulation effects in erbium doped fiber amplifiers (EDFAs). These effects arise due to sudden input power changes at network reconfiguration or system faults. An extended nonlinear model of the EDFA is derived, including amplified spontaneous emission (ASE). Two novel EDFA control applications are developed and compared: one based on L_2 nonlinear control and the other based on optimized gain scheduling. The design of each control law is subject to realistic physical constraints as encountered in industrial application.

Keywords: Nonlinear control; PID controllers; Linearization; Optical amplifiers; Optical fiber networks; Interpolation approximation

1. Introduction

Regarded as the greatest innovation since optical fiber in the past decade, the erbium doped fiber amplifier (EDFA) has revolutionized the optical communication industry by enabling amplification of many lightwave channels simultaneously (Ramaswami & Sivarajan, 2002). An EDFA is an optical fiber usually a few meters in length that has been doped with erbium ions (Er^{3+}) (Giles & Desurvire, 1991). However, there are a number of challenges that must be overcome as WDM optical networks are transformed from static point-to-point systems into dynamic, reconfigurable networks, and EDFA control is one such challenge. When information is dynamically routed through fiber links (Ramaswami & Sivarajan, 2002), data channels are expected to be added and dropped at designated points in the network with minimal power transients occurring (Srivastava, Sun, Zyskind, & Sulhoff, 1997; Sun & Srivastava et al., 1997). During channel add/drop, the EDFA suffers from cross-gain modulation which induces power transients on surviving channels (Sun, Zyskind, & Srivastava, 1997). These unwanted power transients are detrimental to channel performance and control schemes have been realized to reduce them (Ding & Pavel, 2005; Motoshima et al., 1997, 2001; Sun & Zyskind et al., 1997). Though effective, these methods lack a systematic consideration of plant characteristics, virtually all being based on conventional proportional-integral-derivative (PID) and linearization techniques. The EDFA is a nonlinear, multivariable system, whose behavior is highly dependent on its operating point. Thus, there is a need for more systematic and sophisticated control that results in robust and dynamic EDFA devices operating over a wide range of conditions. This is the problem that is addressed in this paper. Preliminary results appeared in Stefanovic and Pavel (2005) and Ding and Pavel (2005).

Current control design approaches start with a linearized EDFA model and ignore the amplified spontaneous emission (ASE) noise. The EDFA model is developed here as a full nonlinear system with ASE. Based on this extended, nonlinear EDFA model, two control schemes are developed. The first one is a nonlinear L_2 control scheme based on (Doyle, Francis, & Tannenbaum, 1993; Doyle, Glover, Khargonekar, & Francis, 1989; Khalil, 2002; Lu & Doyle,

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1993; van der Schaft, 1991, 1992) that minimizes the variation of the average inversion level. This ensures that the channel gains remain constant. The second control scheme is used for comparison and it is an optimized gain scheduling approach. Instead of interpolating among several pre-designed controllers, a single parameterized PID controller is derived based on the known EDFA system model. The two control schemes are compared via simulations. The L_2 nonlinear control shows promising results when compared to the gain scheduled PID, producing faster and smoother transient responses. This paper presents an example of a practical industrial problem tackled by using L_2 nonlinear control.

This paper is organized as follows. In Section 2, an extended EDFA model is developed that includes the effect of ASE. In Section 3, the design specifications are stated and the two control schemes are developed. Simulation results from the two schemes are compared and contrasted in Section 4, followed by conclusions.

2. Plant specification and modeling

2.1. EDFA model with ASE

In this section, a state-space model for the EDFA including the ASE contribution is developed. As a starting point, the steady-state nonlinear model (Feng et al., 2002) and the basic propagation and rate equations in Giles and Desurvire (1991) are used. This new extended EDFA model will be used for control design.

The basic mechanisms in an EDFA are stimulated emission, which amplifies the signal, and spontaneous emission, which causes noise (Agrawal, 1997; Giles & Desurvire, 1991). ASE is the result of excited atoms releasing energy without stimulus from the input channel powers and it produces noise (Ramaswami & Sivarajan, 2002). ASE can have a significant effect under certain conditions of EDFA operation and manifests itself prominently with higher average inversion levels (Agrawal, 1997). A large channel drop increases the magnitude of the ASE present on the output channels.

Let $n_i(r,\phi,z)$ for $i=1,2,t$ denote the ground state, excited state and total erbium ion populations, respectively, with $n_1+n_2=n_t$. Also, let i_k denote the normalized optical intensity. Here r is the radius, ϕ is the azimuth angle, and z is the distance along the EDFA fiber (Giles & Desurvire, 1991). $P_k(z)$ will denote the power of the kth beam of light, or the channel power, as a function of distance along the EDFA fiber. Let v_k denote the frequency of the light beam centered at $\lambda_k = c/v_k$ and σ_{ak} and σ_{ek} are the absorption and emission cross sections, respectively.

The EDFA rate and propagation equations (Giles & Desurvire, 1991) are

$$\frac{\mathrm{d}n_2}{\mathrm{d}t} = \sum_k \frac{P_k i_k \sigma_{ak}}{h v_k} n_1(r,\phi,z) - \sum_k \frac{P_k i_k \sigma_{ek}}{h v_k} n_2(r,\phi,z) - \frac{n_2(r,\phi,z)}{\tau_o}, \tag{1}$$

$$\begin{aligned}\frac{\partial P_k}{\partial z} &= u_k \sigma_{ek} \int_0^{2\pi}\int_0^{\infty} i_k(r,\phi) n_2(r,\phi,z) r\,\mathrm{d}r\,\mathrm{d}\phi (P_k(z) + m h v_k \Delta v_k) \\ &\quad - u_k \sigma_{ak} \int_0^{2\pi}\int_0^{\infty} i_k(r,\phi)\cdot n_1(r,\phi,z) r\,\mathrm{d}r\,\mathrm{d}\phi (P_k(z)),\end{aligned} \tag{2}$$

where τ_0 is the spontaneous lifetime of the excited erbium atoms, u_k represents either the forward (+1) or reverse (−1) direction of propagation through the EDFA. m represents the number of modes in the fiber, and set to 2 here. Δv_k represents the effective noise bandwidth, and is set to 100 GHz here.

Eqs. (1) and (2) by themselves cannot be used for control. In Feng et al. (2002), a model was derived that includes an ASE term, but it was not placed in state-space form, nor was the ASE term used. In Appendix, a new extended EDFA model with ASE in state-space form is derived, given in its final form as

$$\begin{aligned}\dot{x} &= -\frac{x}{\tau_o} - \frac{1}{\zeta\tau_o L}\sum_k \Bigg(-g_k m \Delta v_k L x + u_k \Bigg[\frac{-g_k m \Delta v_k x}{(\alpha_k+g_k)x-\alpha_k} \\ &\quad \times (1 - \mathrm{e}^{u_k\{(\alpha_k+g_k)x-\alpha_k\}L}) + (\mathrm{e}^{u_k\{(\alpha_k+g_k)x-\alpha_k\}L} - 1) Q_k^{in} \Bigg]\Bigg),\end{aligned}$$

$$\begin{aligned}Q_k^{out} &= \frac{-g_k m \Delta v_k x}{(\alpha_k+g_k)x-\alpha_k}[1 - \mathrm{e}^{u_k\{(\alpha_k+g_k)x-\alpha_k\}L}] \\ &\quad + \mathrm{e}^{u_k\{(\alpha_k+g_k)x-\alpha_k\}L} Q_k^{in},\end{aligned} \tag{3}$$

where $x = \overline{N_2}(t) = 1/L\int_0^L N_2(z,t)\,\mathrm{d}z$ is the average inversion defined as the average fraction of atoms in the upper energy level, and Q_k^{in} and Q_k^{out} represent the normalized input and output powers of the kth EDFA channels, respectively.

The standard EDFA model (Sun & Zyskind et al., 1997), typically used for PID control is

$$\begin{aligned}&\rho S L\left(\frac{\mathrm{d}}{\mathrm{d}t} + \frac{1}{\tau_o}\right)x = Q_{pump}(t) - \sum_{k=1}^{N} Q_k^{in}(t)\{\mathrm{e}^{[((g_k+\alpha_k)x-\alpha_k)L]} - 1\}, \\ &Q_k^{out}(t) = Q_k^{in}(t)\,\mathrm{e}^{[((g_k+\alpha_k)x-\alpha_k)L]} \quad k=1,\ldots,N,\end{aligned} \tag{4}$$

$$G(t) = \frac{Q_{total}^{out}(t)}{Q_{total}^{in}(t)},$$

where

$$Q_{total}^{in}(t) = \sum_{k=1}^{N} Q_k^{in}(t), \quad Q_{total}^{out}(t) = \sum_{k=1}^{N} Q_k^{out}(t)$$

with $G(t)$ being the total gain.

The new EDFA model (3) shows some interesting features when compared to the simplified model (4). There are two new terms in the state equation, and one new term in the output equation in (3). These terms are due to ASE contribution and they are independent of the input power.