Application of H_∞ Control on Pilot Tones in Erbium-Doped Fiber Amplifiers

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Abstract: We propose the design and use of an H_∞ controller to suppress the effects of cross gain modulation due to supervisory pilot tones within Erbium-Doped Fiber Amplifiers. Transient response improvements are shown through simulation.

OCIS codes: (060.2410) Fibers, erbium; (060.2320) Fiber optics amplifiers and oscillators; (140.4480) Optical amplifiers

1. Introduction

The application of Erbium-doped fiber amplifiers (EDFA) within wavelength-division multiplexed (WDM) systems has enabled significant improvements in network capacity, reliability and transparency. However, it is well known that EDFAs suffer from the effects of cross-gain modulation, whereby output signals exhibit unwanted power transients due to varying input signal powers entering the EDFA [1,2]. Moreover, these transient effects become more pronounced as the signal transverses across the network.

Up to this point the analysis and control of these transients have been primarily for a single type of input signal disturbance—the addition and removal of channels from the network due to network reconfiguration or network faults [3,4]. Although gain control methods have shown to be effective, there have been no attempts to analyze the robustness or optimality of these control methods with respect to different types of disturbances. Specifically, by modulating each channel with a unique pilot tone each incoming optical signal can be monitored and tracked all-optically [5-7]. However, these pilot tones lead to unwanted ghost tones on surviving channels.

In this paper we propose the design and use of an H_∞ controller for gain compensation to improve optical performance in light of these pilot tone disturbances. We provide simulation results for a single stage EDFA showing significant improvements in transient behavior.

2. EDFA Model and Pilot Tone Description

The rate equations for average inversion [8] describe the dynamic behavior of an M channel EDFA. By linearizing around a nominal operating point (N_{20} , p_{in0} , p_{out0} , p_{p0}) the EDFA can be further described by the state-space model (1), with average inversion N_2 as the state variable, input p_{in} and output p_{out} channel power as the respective M-dimensional input and output vectors, average total gain y_G as the measurement variable and pump power p_p as the control variable [9].

$$EDFA:\left\{\begin{bmatrix} \partial N_2 / \partial t \\ p_{out} \\ y_G \end{bmatrix} = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix} \begin{bmatrix} N_2 \\ p_{in} \\ p_p \end{bmatrix}\right. \tag{1}$$

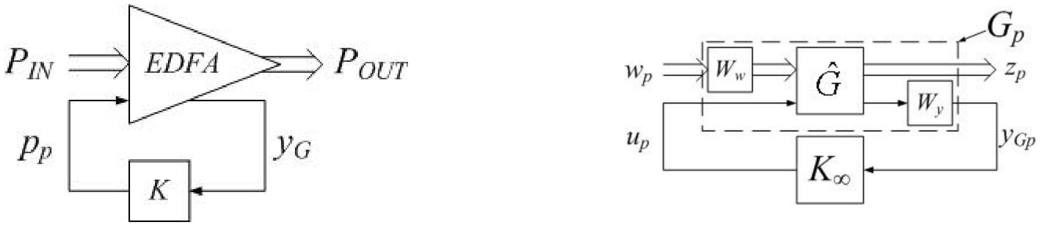
We then proceed to describe the optical power of an i^{th} channel modulated with a pilot tone by (2) where P_0 is the nominal optical power, m_i is the modulation depth, $f_{c,i}$ is the pilot tone frequency, Δf is the peak frequency deviation and $d_i(t)$ is the binary (NRZ) data carried on the pilot tone.

$$P_i(t) = P_0\left[1 + m_i \cdot \sin(2\pi(f_{c,i} + \Delta f \cdot d_i(t))t)\right] \tag{2}$$

Typically pilot tone frequencies f_c are selected such that they do not interfere with the natural low frequency gain dynamics of the EDFA, while also remaining below the high speed transmission bandwidth [5-7]. Also in order to avoid power penalty at the receiver, modulation depth is limited to 10% of the data level [5-7].

3. H_∞ Control Problem and Design

From the state space description in (1), we map the EDFA configuration in Fig. 1a) to a general feedback control problem, using the average total gain to adjust the EDFA's pump power. We augment the plant G to $\hat{G}$ to meet the H_∞ control assumptions in [10] and then proceed to weight the EDFA with the disturbance weighting W_w, to describe the system's pilot tones, and measurement weighting W_y, to impose integral control. We select a band pass filter shape to describe the band of frequencies where the pilot tones reside (100Hz-1MHz) for W_w.



(a) (b)

Fig. 1. EDFA Control configuration (a) mapped to a weighted H_∞ control problem (b)

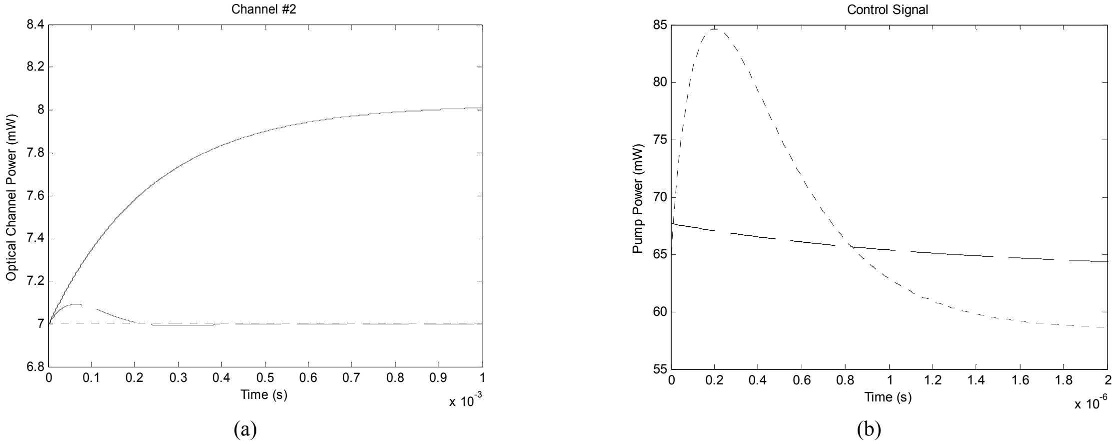
Given the weighted EDFA plant G_p as shown in Fig. 1b) we attempt to minimize the H_∞ norm of the closed loop transfer function T_{zw} from the disturbance variable w_p (input power) to the performance variable z_p, taken to be the average inversion level. That is, we synthesize a controller K_∞ such that $||T_{zw}||_\infty < \gamma$, for some $\gamma > 0$.

4. Simulation Results

For our numerical simulations, we consider a single stage 10 channel L-Band EDFA. Under nominal operating conditions, all input channels are ON, operating with an average optical power of 0.341mW with the EDFA providing an average gain of 13dB per channel. The EDFA is pumped at 980nm with a nominal pump power of 65 mW. For our simulations we compare the transient response of the uncontrolled EDFA, H_∞ controlled EDFA and a traditional PID controller, as defined in [9].

4.1 Channel Add/Drop

To simulate a channel drop we apply a negative step on channel 1. Fig. 2a) shows the transient response of the surviving output power on channel #2.



(a) (b)

Fig. 2. EDFA Transient response for a channel drop on channel 1. (a) Power excursion on surviving channel #2 for uncontrolled EDFA (solid), PID Controlled EDFA (dashed) and H_∞ controlled EDFA (dotted). (b) Required pump power for gain compensation for PID Controlled EDFA (dashed) and H_∞ controlled EDFA (dotted).

Immediately we notice significant improvements in response time, maximum power excursion and steady state error when either controller is used. The H_∞ controller exhibits a response time of 1.5μs, compared to a response time of 0.5 ms for the PID controlled EDFA. Also the H_∞ controller improves upon the maximum power excursion of the PID controller by approximately 90%. Fig. 2b) illustrates the rate of pump power which is required to achieve this level of performance. The PID controller requires an additional 7mW within 0.1ms, while the H_∞ controller requires a boost of 19mW within 0.2μs.

4.2 Pilot Tone Response

In our simulation, we modulate pilot tones onto both channel 1 (f_{c1} = 20kHz, m_1 = 0.05) and channel 2 (f_{c2} = 5.0kHz, m_1 = 0.1). Fig. 3. compares the response on channel 3. When compared against the uncontrolled EDFA the PID controller reduces the power excursion by 25%, whereas the H_∞ controller reduces the power excursion by 75%.

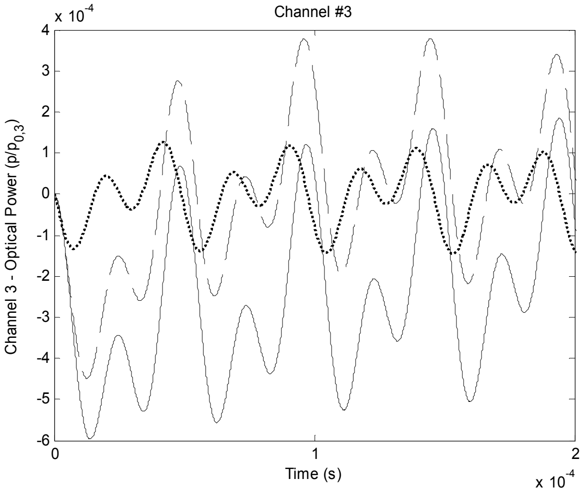


Fig. 3. EDFA Pilot Tone response for surviving channel #3: uncontrolled EDFA (solid), PID Controlled EDFA (dashed) and H_∞ controlled EDFA (dotted).

5. Conclusions

This paper presented the application of a H_∞ controlled EDFA for suppression of power transients owed to pilot tones. Simulation and analysis of power transients is shown to provide significant performance improvements, reducing power excursion and response time.

6. References

[1] C.R. Giles and E. Desurvire, "Transient gain and crosstalk in erbium-doped fiber amplifiers," Optics Letters, **14**, 880-882 (1989).
[2] A. K. Srivastava, Y. Sun, J.L. Zyskind and J.W. Sulhoff, "EDFA transient response to channel loss in WDM transmission system," IEEE Photon. Letters, **9**, 386-389 (1997).
[3] A.K. Srivastava, J.L. Zyskind et al., "Fast-link control protection of surviving channels in multiwavelength optical networks," IEEE Photon. Letters, **9**, 1667-1669 (1997).
[4] M. Zirngibl, "Gain control in erbium-doped fiber amplifiers by an all-optical feedback loop," Electron. Lett., **27**, 560-561 (1991).
[5] F. Heismann, M. T. Fatehi, S. K. Korotky, and J. J. Veselka, "Signal tracking and performance monitoring in multi-wavelength optical networks," Proc. ECOC, Oslo, Norway, 47-50 (1996).
[6] G. R. Hill et al., "A transport network layer based on optical network elements," Journal of Lightwave Tech., **11**, 667-678 (1993).
[7] H. C. Ji, K. J. Park, et al., "Optical performance monitoring techniques based on pilot tones for WDM network applications," Journal of Optical Networking, **3**, 510-533 (2004).
[8] Y. Sun, J. L. Zyskind and A. K. Srivastava, "Average inversion level, modeling and physics of erbium-doped fiber amplifiers," IEEE J. Sel. Topics in Quant. Electr., **3**, 991-1007 (1997).
[9] L. Pavel, "Control design for transient power and spectral control in optical communication networks," Proc. IEEE Conference for Control Applications, 415-422 (2003).
[10] J.C. Doyle, K. Glover, P.P. Khargonekar and B.A. Francis, "State-space solutions to standard H_2 and H_∞ control problems," IEEE Trans. On Automatic Control, **34**, 831-847 (1989).