An EDFA H_∞ Controller for Suppression of Power Excursions Due to Pilot Tones and Network Traffic

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***Abstract*—Conventional erbium-doped fiber amplifier (EDFA) control schemes lack a systematic design approach and do not consider the characteristics of input disturbances. We propose the application of H_∞ control to suppress cross-gain modulation effects due to pilot tones and network burst-switched traffic. A detailed design of the EDFA H_∞ controller is given, focused on input disturbance characteristics and desired performance measures. Simulation results under different types of disturbances show significant improvements in response time and power excursion reductions.**

***Index Terms*—Burst traffic, optical amplifier, optical networks, optimal control.**

I. INTRODUCTION

CONTROL and management of erbium-doped fiber amplifiers (EDFAs) is an important design problem in the evolution towards a dynamic optical network [1]. As wavelength-division-multiplexed networks increase in complexity, there remain a number of challenges, such as dealing with disturbances related to intrinsic network characteristics. For example, as channels are added–dropped from the network, EDFA cross-gain modulation induces power transients in surviving channels [2], [3], which propagate through the network. Several control schemes have been realized to address them [4]–[6], [14], [15]. Though effective, these control methods lack a systematic design approach; most use traditional proportional integrator derivative (PID) control, or need feed-forward perfect cancellation. Moreover, there have been no formal attempts to analyze the robustness or optimality of these control schemes with respect to different types of disturbances and performance objectives. In this letter, we propose the design and application of H_∞ control to minimize the effects of input signal disturbances upon EDFAs. Part of this work appeared in [16]. Via H_∞ control, by incorporating in design what is known of the input disturbances, we can provide a measure of robustness for the EDFA under a range of conditions. The synthesis of H_∞ optimal controllers involves a systematic yet simple methodology, available in MATLAB.

II. SIGNAL DISTURBANCES

In addition to channel addition or removal, two other types of signal disturbances arise in optical networks: pilot tones and burst-mode traffic. Pilot tones are used to track and monitor the performance of individual channels [7]. Binary data can be frequency modulated upon the pilot tone, useful for signal routing. Channel optical power modulated with a pilot tone is given as $P_i(t) = P_0\,[1 + m_i \sin 2\pi(f_{c,i} + \Delta f d_i(t)t)]$, where P_0, m_i, f_{ci}, $\Delta f, d_i(t)$ are nominal optical power, modulation depth, tone frequency, peak frequency deviation, and binary data. Tone frequencies are typically set above EDFA's natural gain dynamics, and below the link's payload, i.e., between 10 and 100 kHz. Tone amplitude is below 10% of average power to avoid large penalties. However, due to cross-gain modulation these pilot tones induce ghost tones on surviving channels which may be mistaken as pilot tones at the receiver [8]. Optical burst switching (OBS) allows for efficient resource sharing amongst numerous users [9]. In burst -mode traffic input channel powers are turned ON and OFF for random lengths of time. As input traffic approaches self-similarity, burst lengths become comparable to EDFA's natural response time, leading to sizable output power swings [10]. Self-similar traffic can be modeled as in [10] whereby channel's input power is modeled as a succession of ON (full power) and OFF (zero power) periods. Each ON–OFF period is a random variable with Pareto distribution $T_i = \lfloor 1/U^{1/\psi}i \rfloor$, where U has uniform distribution on $[0,1]$ and ψ_i measures traffic variability $i = \{\mathrm{ON}, \mathrm{OFF}\}$. Network utilization is $\rho = E[T_{\mathrm{ON}}]/(E[T_{\mathrm{ON}}] + E[T_{\mathrm{OFF}}])$. Various network traffic can be modeled by varying ρ and ψ_i, e.g., $1 < \psi_i < 2$ for self-similar traffic $\psi_i \gg 2$ for smooth traffic.

III. EDFA H_∞ CONTROL DESIGN

H_∞ control provides simple, reliable, and robust controllers [12], [16], minimizing the H_∞ norm from input disturbances w to some designed performance signals z. We map the EDFA to the H_∞ control problem, by linearizing the nonlinear EDFA equations [11] around a nominal operating point and normalizing system variables. The average inversion level is modeled as the internal state x normalized input channel powers as disturbance w, average gain as measurement v, and EDFA's pump power as control u. As performance variable we select $z = x$ to minimize the norm from input signal disturbances to EDFA's average inversion. This EDFA model is augmented to G to meet the H_∞ assumptions and weighting functions are designed to shape the frequency response: $W_w(s)$ for input disturbances and $W_y(s)$ for minimum steady-state error (see [16] and [17] for more details). W_w is modeled as a bandpass filter $W_w = k_w w_H s/(s + w_L)(s + w_H) + \alpha_w$, with w_L, $w_H = 2\pi f_{\min}$, $2\pi f_{\max}$ to describe the input disturbances' bandwidth, $k_w < 1$, $\alpha_w = 1 + m_{\max}$ for their maximum amplitude, where $m_{\max}$ is the maximum modulation index. W_y is realized as a bi-proper function $W_y = (\beta_y s + 1)/(s + \alpha_y)$ resulting in approximate integral control, with $\beta_y \ll 1/f_{\max}$ and $\alpha_y \ll f_{\min}$. This yields a weighted augmented plant G_p (Fig. 1) for which a controller K_∞ can be synthesized via the H_∞ algorithm [12]. Combining

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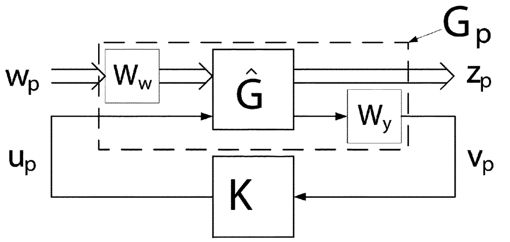

Fig. 1. Weighted augmented EDFA for H_∞ controller synthesis.

TABLE I
CONTROLLER SYNTHESIS PARAMETERS

Parameter	Expression	Value	Unit
Max Acceptable Power Excursion		10	%
Min Frequency Disturbance	f_{min}	100	Hz
Max Frequency Disturbance	f_{max}	10×10^6	Hz
Max modulation depth	m_{max}	0.1	-
Control Signal Penalty		0.001	-

K_∞ with the measurement weighting W_y gives the controller $K = K_\infty W_y$ to be used on the EDFA.

IV. SIMULATION RESULTS

We consider a 16-channel C-band EDFA with 14-dB average gain and 150-mW nominal pump power. Channels are evenly spaced from 1544 to 1559 nm, with 0.1995-mW nominal input channel power. Controller parameters are chosen as in the Table I. We generate the weighted G_p and synthesize via MATLAB a fifth-order H_∞ controller K_∞ and the EDFA controller $K_{II} = K\infty W_y$. The response of the closed loop EDFA is observed under three test cases (channel add–drop, pilot tones, and network traffic disturbances), for three different control cases: uncontrolled $(u = 0)$; PID controller (K_{PID}) and H_∞; controller (K_{II}). The PID controller has a standard cascade form $K_{\mathrm{PID}} = k(1 + \tau_1 s)(1 + \tau_2 s)/\tau_1 s(1 + 0.1\tau_2 s)$, [14], with τ_1, $\tau_2 = 0.3\tau_1$ optimized to give a phase margin of 50° (for details see [17]).

In a standard channel drop test case, a step input power drop is applied on Channel 2 from nominal value to zero, and output power excursions are monitored on Channel 1. The transient response is significantly improved with the H_∞ controller versus the PID controller: a settling time of 4.2 μs compared to 100 μs, and maximum power excursion reduced by approximately 80%. For pilot tone test case Channels 2, 3, and 4 have pilot tones modulated onto, with $fc, i = \{20, 10, 100\}$ kHz, $m_i = \{0.1, 0.05, 0.08\}$, $\Delta f = 1$ kHz. We are interested in minimizing the cross-response on surviving channels (Fig. 2). The H_∞ controller K_{II} improves the performance significantly: maximum power excursion is reduced by 20 and 15 dB, versus the uncontrolled and PID controller. The PID controller is best suited for step type disturbances (due to the integrator action). When used for the pilot tone case (Fig. 2 with pilot tone applied at $t = 0$), the PID generates an initial overshoot due to an overcorrection when acting for a sinusoidal-type disturbance. Its settling time is 100 μs, and due to this initial overshoot, the transient response of the PID controller is worse than in the uncontrolled case until about 70 μs (Fig. 2). For the network traffic case we assume that four channels (2, 6, 10, 14) are in burst -mode and analyze cross-gain effects on Channel 1.

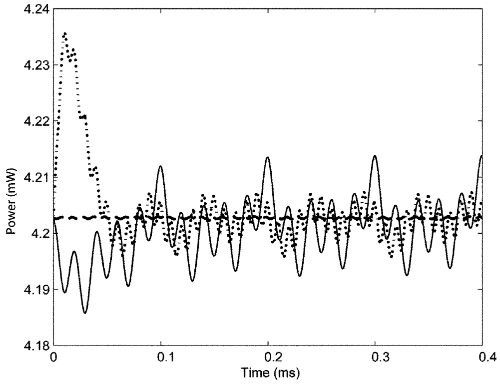

Fig. 2. Pilot tone response under different control cases: Uncontrolled case (solid line); *KP ID* controller (dotted line); *KII* controller (dashed line).

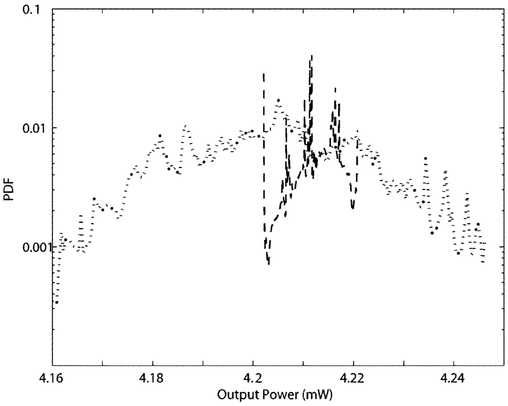

Fig. 3. 25% load, 1 Gb/s, burst traffic: *KP ID* controller (dotted line); *KII* controller (dashed line).

All burst lengths are multiples of 53 bytes (one asynchronous transfer mode (ATM) cell with cell length of 0.4 μs). The responses are simulated for 1000 cells (0.1 million samples). We plot 100 points per cell, enough to capture the power excursions for all control schemes (Figs. 3–6). All burst mode channels have 50% utilization $(\rho = 0.5)$; $\psi_{\mathrm{ON}} = \psi_{\mathrm{OFF}} = 1.2$ for self-similar traffic, and $\psi_{\mathrm{ON}} = \psi_{\mathrm{OFF}} = 5.0$ for smooth traffic. We measure the dynamic power swings on Channel 1 by the probability distribution function (PDF), for both the PID and H_∞ controller. Fig. 3 shows the PDF results for the nominal case (four OBS channels with self-similar traffic in a 1-Gb/s link (25% load). With the H_∞ controller, the power swings are kept to under 0.02 mW at a probability of 10^{-3}, while with the PID control power swings in excess of 0.085 mW are seen. To test robustness of the control scheme, we simulate different traffic, to see how power swings vary with disturbance characteristics. Figs. 4 and 5 show results for traffic in a high-speed 25-Gb/s link, and for 100% load (all channels with OBS traffic). Smooth traffic produces the smallest power swings (Fig. 6) as in [10] and [13]. The H_∞ and PID controllers have different design specifics, such as the H_∞ constraint of approximate integral control. Thus, in Figs. 3–6 the peak positions of the PDF (steady-state power) are slightly different in the two cases. The 100% load results in large power swings under uncontrolled and PID controlled EDFA schemes (Fig. 5), due to the choice of nominal case (25% load, 1-Gb/s link). In the 100% load OBS case, all channels are allowed to turn OFF, thus the total input

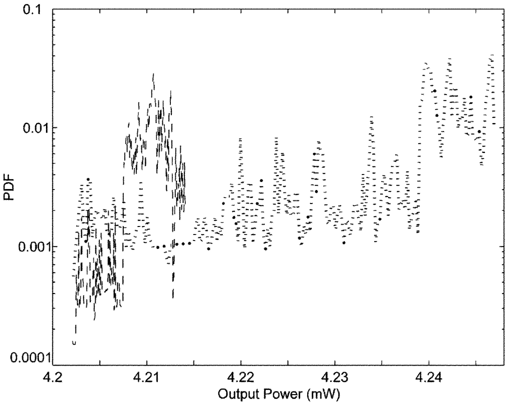

Fig. 4. 25% load, 25 Gb/s, burst traffic: *KP ID* controller (dotted line); *KII* controller (dashed line).

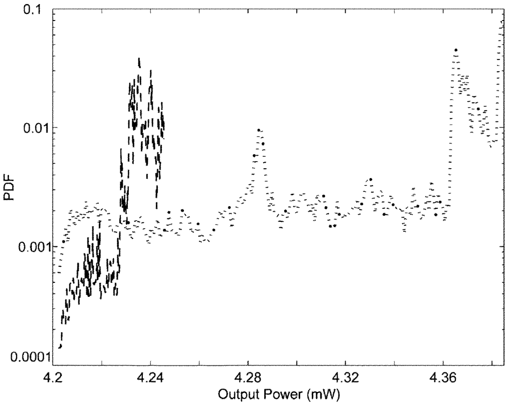

Fig. 5. 100% load, 1 Gb/s, burst traffic: *KP ID* controller (dotted line); *KII* controller (dashed line).

power is expected to have larger variations compared to 25% load case. Moreover, the PID controller shows variation in performance (different PDF shape) as the frequency of input power variation increases from 1 to 25 Gb/s (Figs. 3 and 4). The cell length and burst length in Fig. 4 are 1/25 of those in Fig. 3, and the PID controller does not allow sufficient gain recovery in this case due to its relatively slow response. Overall, under all cases the H_∞ controller provides the largest reduction in power swings; both PID controlled and uncontrolled EDFA exhibit power swings dependent upon network traffic characteristics.

V. CONCLUSION

We proposed an optimal H_∞ controller to reduce the effects of cross-gain modulation within EDFAs, due to pilot tones, OBS network traffic in addition to channel add–drops. We systematically designed the H_∞ controller, incorporating knowledge of input disturbances. We compared the H_∞ controller with a PID controller, both designed for a given EDFA operating point. Via simulations, we showed significant performance improvements. For pilot tone disturbances, the appearance of ghost tones is reduced by 80% when compared to a PID controller. Under various network traffic cases the H_∞ controller reduces power swings by more than 50%. Gain scheduling techniques can be used to adapt the H_∞ controller for different EDFA operating conditions [17].

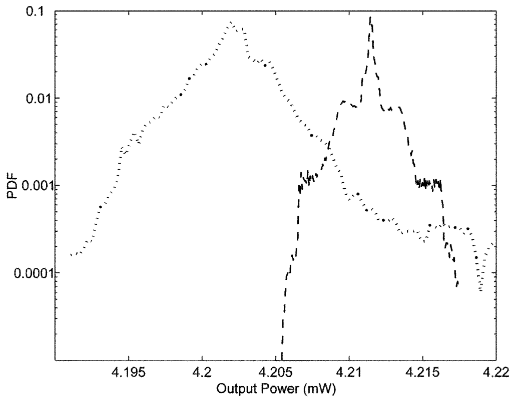

Fig. 6. 25% load, 1 Gb/s, smooth traffic: *KP ID* controller (dotted line); *KII* controller (dashed line).

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