Adaptive Control of Mode-Dependent Gain in Multi-Mode Erbium-Doped Fiber Amplifiers

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***Abstract*—We demonstrate adaptive control of mode-dependent gain in a multi-mode erbium-doped fiber amplifier by placing a spatial light modulator in line with the pump laser.**

I. Introduction

As LONG-HAUL single-mode fiber systems approach information-theoretic limits [1], spatial multiplexing in multi-mode or multi-core fibers offers a possible route to higher throughput [2]. The properties of transmission fibers and fiber amplifiers are crucial to the ultimate feasibility of spatially multiplexed long-haul systems. In transmission fibers, low group delay spread minimizes receiver signal processing complexity [3], while large modal effective areas minimize nonlinear effects. In fiber amplifiers, low mode-dependent gain (MDG) minimizes the loss of capacity and the potential for outage [4].

Several approaches have so far been proposed for controlling MDG in multi-mode erbium-doped fiber amplifiers (MM-EDFAs). One approach would be to use an optimized erbium doping profile in the MM-EDFA [5]. While this approach can greatly reduce MDG when implemented perfectly, imperfections in fiber fabrication or pumping can lead to increased MDG values. An alternate approach is to control the modal content of the pump by passing several variable-power pump beams through phase masks and combining them using beam splitters [6]. The loss of beam splitters makes this method increasingly inefficient as the number of pump beams is increased, as might be required to accommodate an increasing number of signal modes.

We present a new scheme for adaptive control of MDG in MM-EDFAs by controlling the modal content of the pump using a spatial light modulator (SLM). This technique can be used in MM-EDFAs with either uniform or more complex erbium doping profiles. Our technique is more power-efficient than the previous methods of controlling the modal content of the pump as it only requires one pump laser per polarization, independent of the number of signal modes.

Here, we study MM-EDFAs for signals spatially multiplexed in 12 modes (six spatial modes in two polarizations). By numerical solution of multi-mode rate equations, we compare MDGs obtained before and after optimizing the SLM.

In a practical system, wavelength-dependent gain also needs to be controlled. This may be done in the MM-EDFA using gain-flattening filters [7], or elsewhere in the network using appropriately designed multi-mode dynamic gain equalizers.

II. Adaptive Control of MDG

A. Multimode Fiber Amplifier

We consider a MM-EDFA with a uniform erbium doping profile. Bi-directional, dual-polarization end pumping through dichroic couplers would facilitate the high pump powers required for multiple modes and wavelengths. Here we model the simpler case of a co-propagating pump, in order to speed up simulations.

We numerically compute linearly polarized (LP) signal and pump modes in one polarization under the weak-guidance approximation that is appropriate for small numerical apertures (NAs). The multi-mode amplifier power rate equations are [5]:

$$\frac{dP_{s,k}}{dz} = P_{s,k}\int_0^{2\pi}\int_0^{r_d}\left[\sigma_e(\lambda_s)N_2(r,\varphi,z)-\sigma_a(\lambda_s)N_1(r,\varphi,z)\right]\left|\psi_{s,k}(r,\varphi)\right|^2 r\,dr\,d\varphi$$
$$\frac{dP_{p,l}}{dz} = -P_{p,l}\sigma_a(\lambda_p)\int_0^{2\pi}\int_0^{r_d} N_1(r,\varphi,z)\left|\psi_{p,l}(r,\varphi)\right|^2 r\,dr\,d\varphi\,, \quad (1)$$

where $P_{s,k}(z)$ and $P_{p,l}(z)$ describe the evolution of the k^{th} signal mode (k = 1, ..., $k_{\max}$) at wavelength λ_s, and the l^{th} pump mode (l = 1, ..., $l_{\max}$) at wavelength λ_p, respectively over amplifier length z; $\psi_{s,k}(r,\varphi)$ and $\psi_{p,l}(r,\varphi)$ are the corresponding normalized LP field profiles. r_d is the maximum radius at which the fiber in MM-EDFA is doped. $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ are the wavelength-dependent absorption and emission cross sections of erbium ions, respectively. $N_1(r,\varphi,z)$ and $N_2(r,\varphi,z)$ are the local concentrations of erbium ions at lower and upper energy levels, respectively.

B. Measures of MDG

We start by considering a single amplifier, neglecting any frequency dependence of the MDG. The overall MDG is described by the singular values of the amplifier field transmission matrix $\mathbf{M}_{\text{amp}}$, or equivalently, by the eigenvalues

This research was supported by National Science Foundation Grant Number ECCS-1101905 and Corning, Inc.

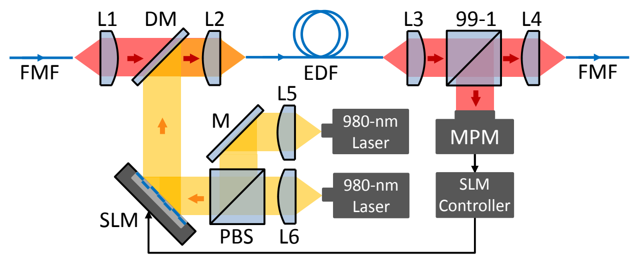

Fig. 1. Adaptive control of MDG in MM-EDFA using an SLM in line with the pump. Gain-flattening filter and isolator are not shown here.

of $\mathbf{M}_{amp}\mathbf{M}^{\dagger}_{amp}$ [4]. We have verified via simulations that there is negligible mode coupling in MM-EDFAs, so the eigenvalues of $\mathbf{M}_{amp}\mathbf{M}^{\dagger}_{amp}$ are simply the power gains of individual modes at the amplifier output.

A more complex system will involve the cascade of many amplification nodes. Assuming random unitary coupling in the fiber between any two successive nodes, the MDG of these nodes will have independent eigenvectors and the overall MDG will accumulate as described in [4]. Hence, in order to predict the performance of a complex system, it is only necessary to characterize the performance of one amplification node.

C. *Adaptive MDG Control using a SLM*

Fig. 1 shows our proposed scheme for the adaptive control of MDG. Two orthogonally polarized pumps are combined using a polarizing beam splitter and illuminate a phase-only SLM. The beam reflected from the SLM is coupled into the EDF using a dichroic mirror and a lens. The SLM controls the electric field pattern of the pump at the input of the EDF. While it is possible to control each polarization separately, for simplicity, we control the two polarizations jointly, assuming a polarization-independent MEMS SLM. To first order, the amplifier gain is the same for pairs of degenerate modes that correspond to the LP modes in orthogonal polarizations; therefore, common control of both polarizations compensates MDG to first order.

At the output of the EDF, a small fraction (e.g., 1%) of the total power is redirected to a modal power meter (MPM). The MPM employs a mode demultiplexer and multiple power meters. The MPM extracts an error signal that is the peak-to-peak MDG variation and passes it to the SLM controller. The SLM controller then uses the adaptive algorithm described in the next section to optimize the SLM phases such that the error signal is minimized and MDG is equalized.

III. Simulation Results

The phase-only SLM comprises a two-dimensional array of reflective pixels. Multiple pixels are grouped into larger disjoint square blocks. The optimization algorithm is a four-phase sequential coordinate ascent (4PSCA). At each step a single SLM block is chosen, and its phase is optimized over the set $\{0, \pi/2, \pi, 3\pi/2\}$ to minimize the error signal. Then the next SLM block is selected and the process is repeated. In all our simulations the algorithm converged after one pass over the SLM blocks.

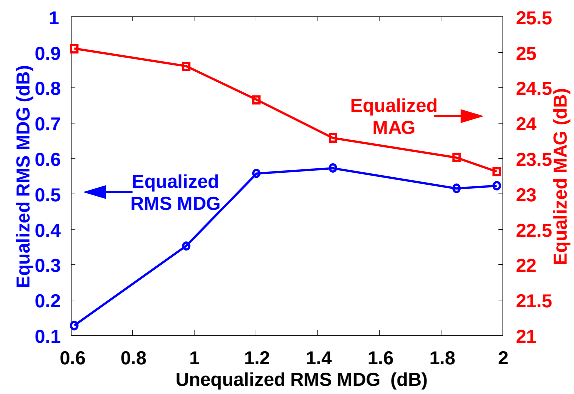

Fig. 2. Equalized RMS MDG and MAG versus unequalized RMS MDG in a 12-mode EDFA.

In simulations, we take the input signal to the MM-EDFA to be continuous-wave at a single wavelength λ_s = 1550 nm, with equal input powers in 12 modes (6 spatial modes in each polarization). The pump wavelength is λ_p = 980 nm, and the pump power is adjusted to yield initially a mode-averaged signal gain of 25 dB. The amplifier length is chosen to be the value of z at which the amplified signal power reaches its maximum. The EDF has a graded-index, depressed cladding (GIDC) profile with 13.2-μm core radius, NA = 0.15 and a uniform 10^{19} cm^{-3} erbium concentration up to a 14.6-μm radius. The focal lengths of the lenses L5 and L6 in Fig. 1 are changed in the simulations to change the beam waist of the pump laser and generate different values of MDG in the amplifier. For each beam waist, the size of the SLM blocks is chosen such that a set of 64 blocks covers a circle enclosing more than 95% of the energy incident on the SLM, so only these 64 blocks are adapted.

Fig. 2 shows the equalized root-mean-square (RMS) MDG and the mode-averaged gain (MAG) of the MM-EDFA versus the unequalized RMS MDG. The worst-case RMS MDG of 2 dB can be reduced to 0.5 dB using the SLM. The reduced MAG at higher unequalized MDGs results from a reduction in pump coupling efficiency as the pump beam waist changes, and can be compensated by an increase in pump power.

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