Gain Filtering for Single-Spatial-Mode Operation of Large-Mode-Area Fiber Amplifiers

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Gain filtering is a robust method to achieve single-mode operation of large-mode-area fiber amplifiers.

- In a uniformly doped fiber, the fundamental mode saturating the gain experiences less gain than other modes.

- Proper radial tailoring of the gain-doping profile can filter out of higher-order modes without introducing any loss.

- Theoretical calculations show
  - reducing the diameter of the gain-doping profile with respect to the waveguide diameter results in the highest gain for the fundamental mode, regardless of gain-saturation level
  - using a Gaussian gain-doping profile to match the fundamental-mode shape does not work as well as a reduced-diameter flat-top profile

- This gain-filtering concept is power/energy scalable and robust with respect to seed purity, core diameter, and numerical aperture.
Large mode area (LMA) fibers are used for power and energy scaling of fiber amplifier systems

- Peak power limitations derived from nonlinear and damage effects can be overcome by using LMA fibers.

- LMA fibers are multimode, resulting in reduced beam quality.
  - Power coupling between modes becomes worse for larger fiber-core diameters
  - Beam quality of injected seed is critical

- All current high-power results rely predominantly on a single technology (coiled fiber) to generate good beam quality.
  - New techniques are needed!

- Previous work in 1-D waveguides and fibers indicates that gain profiling can lead to modal discrimination for the fundamental mode.*

- In this work, we compare several gain profile geometries, show scaling to large core diameters, and demonstrate the robustness of gain filetering.

A general model can be used to understand modal gain under specific saturation conditions.

- Generally, the intensity distribution of a given fiber mode propagating through an active medium can be written as

\[
\frac{dI_k(r, \phi, z)}{dz} = \frac{g_0(r, z)I_k(r, \phi, z)}{1 + \left| \sum_i E_k(r, \phi, z) \right|^2 / I_{\text{sat}}}
\]

where

\[
I_k(r, \phi, z) = \left| E_k(r, \phi, z) \right|^2 = P_k(z) \left| \Phi_k(r, \phi) \right|^2
\]

- The total optical intensity determines the local gain-saturation behavior.
- The resultant gain for a given mode is determined by the overlap of the mode with the spatially resolved saturated gain.
A simplified model including the spatial properties of the modes and gain can demonstrate first-order behavior

- The differential gain for a specific mode in the fiber is given by the overlap between the mode profile and the saturated gain

Small signal gain  

\[ g_k(z) = \int \int \frac{g_0(r) |\Phi_k(r, \phi)|^2}{1 + I_0(r, \phi, z)/I_{sat}} \, r \, dr \, d\phi \]

Mode profile

Differential modal gain

Optical intensity of fundamental mode

Assume most of the power is in the fundamental mode, as is desired

\[ I_0 \gg \sum_{k \neq 0} I_k \]

- The propagation of modal power is given by

\[ \frac{dP_k}{dz} = g_k(z) P_k(z) \]

- The modal gain is calculated for each mode

A value of \( g_0/g_k > 1 \) for all \( k \) is best for obtaining single-mode operation.
Local gain saturation makes fundamental mode operation difficult in conventional LMA fibers

- Conventional LMA fibers typically have gain doping that fills the entire core
- For high saturation by the fundamental mode, higher-order modes experience more gain due to the overlap between mode and gain profiles
With no radial-gain profiling, the fundamental mode has less gain than all other modes for $I_0/I_{\text{sat}} > 0.1$

- As the gain begins to saturate, lower-order modes experience more gain than the fundamental.
- The more the gain saturates, the more the higher-order modes benefit from the remaining gain near the edge of the waveguide.
A single parameter can be used to assess the impact of gain profiling for parametric analysis

- At each level of saturation $I_0/I_{\text{sat}}$, the maximum value of $g_0/g_k$ is calculated using all transverse modes.

- The resultant quantity of $g_0/g_{\text{max}}$ represents the largest higher-order-mode gain and will be used to analyze various fiber geometries.

![Example](image-url)
Radial-gain profiling can lead to significant differential-gain discrimination by reducing the gain diameter

- Begin with a gain-doping region that is smaller than the waveguide diameter
- The fundamental mode can experience more gain than higher-order modes, even at high saturation, by denying gain near the edge of the waveguide
Reduced-diameter gain can lead to maximum gain for the fundamental mode regardless of saturation level.

- The fundamental-mode gain is larger than all other modes regardless of saturation level for gain diameters ~50%–60% of the waveguide core.
- Single-mode performance can be expected.
Radial-gain profiling can lead to improvements by matching the fundamental-mode profile

- Begin with a doping region that mimics the fundamental-mode profile
- The fundamental mode can experience more gain due to more uniform saturation
A mode-matched gain profile does not offer as high a mode discrimination as reduced-diameter step gain.

- Mode-matched profiles provide gain at larger radii where higher-order modes can benefit, even when saturated by the fundamental mode.

- Therefore, they do not have as high a mode discrimination as reduced-diameter step-gain profiles.
A detailed model of LMA fiber amplifiers* confirms the effectiveness of gain filtering

- The power of each mode (including the pump) follows:

\[
\pm \frac{dP_k}{dz} = \sigma_e(\lambda_k) P_k(z) \int \int |\Phi_k(r, \phi)|^2 n_2(r, \phi, z) dA - \sigma_a(\lambda_k) P_k(z) \int \int |\Phi_k(r, \phi)|^2 n_1(r, \phi, z) dA
\]

- The upper-state population density follows:

\[
\frac{dn_2}{dt} = n_1 \sum_k P_k |\Phi_k(r, \phi)|^2 \sigma_a(\lambda_k)/h\nu_k - n_2 \sum_k P_k |\Phi_k(r, \phi)|^2 \sigma_e(\lambda_k)/h\nu_k - n_2/\tau = 0
\]

where \( n_1(r, \phi, z) + n_2(r, \phi, z) = n_T(r, \phi) \)

Dual-clad fiber amplifiers are modeled using all of the fiber modes and bi-directional pumping

- Physical LMA fiber amplifier geometry

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<tr>
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<th>50 μm</th>
<th>100 μm</th>
<th>800 μm</th>
<th>1600 μm</th>
<th>1 kW</th>
<th>4 kW</th>
<th>1.6 kW</th>
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<td>Core waveguide diameter</td>
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<td>Pump power per end</td>
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<td>Nominal output power</td>
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- Beam purity is defined as the fraction of power in the fundamental mode

- Caveats to simulations
  - spontaneous emission contribution to mode power is neglected
  - mode mixing and coherent addition of modes (speckle) are not included
Gain smaller than the waveguide can lead to excellent output beam quality regardless of seed beam quality.

- For a gain diameter 40\%–80\% of the waveguide diameter, 99\% fundamental mode output can be obtained for reasonable seed purity (>0.9).
- Even for poor seed quality as low as 0.5, 90\% fundamental mode output can be obtained for dopant profiles within a 5\% range of the optimum gain diameter.
Gain filtering can lead to single-spatial-mode operation of large-mode-area fiber lasers and amplifiers

The concept of gain filtering results in a net differential gain that is higher for the fundamental mode than all other modes regardless of saturation level.

- Gain filtering is more efficient than loss filtering because no light is discarded.

- Gain filtering is extremely robust since it depends on the spatial-mode profile rather than the propagation coefficients.
  - robust toward seed-mode purity
  - robust against relative geometrical cross-section dimensions
  - robust against core diameter and numerical aperture
    - the method is power/energy scalable!

- Gain filtering can be designed into existing architectures by leaving the gain diameter fixed and increasing the waveguide diameter.
**Summary/Conclusions**

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Acknowledgements

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