





































of quantum noise the light that best matches the light in LP<sub>01</sub> both in amplitude and phase over the beat cycle. This is the light with highest gain. There will be fluctuations in frequency and power, but the average power within the gain bandwidth will be well approximated by Eq. (53).

## 19. Desktop computer implementation

### 19.1. Memory requirements

Storing the full, four-dimensional double-precision, complex  $[64 \times 64 \times 64 \times L/\Delta z]$  array of the signal field would require on the order of 1 – 10 terabytes in a meter long amplifier with step sizes of a few microns. Therefore, we do not store  $E$  fields at each step. We only store computed properties such as modal content  $F_{m,n}(z, t)$ , total signal power  $I(z, t)$ , and effective area  $A_{\text{eff}}(z, t)$  at positions separated by  $(\Delta_{\text{sample}} \times \Delta z)$ . This reduces the amount of memory required to at most a few gigabytes.

### 19.2. Parallel computing

A substantial portion of the model's run time is spent solving the thermal problem. This makes the Green's function method attractive because it is generally much faster than the ADI method. One reason the ADI is relatively slow is that it is necessary to integrate through several cycles of the heat to ensure steady-periodic condition is enforced.

Equally important, the Green's function method is easy to parallelize while the ADI method is not. The ADI method is sequential by nature. It requires updating the entire grid to advance the time by  $\Delta t$ . In contrast, the Green's function involves a summation of the temperature contribution from each heated pixel, so the calculations for pixels are independent and easy to run in parallel. This parallelization is relatively simple to implement using the shared-memory multiprocessing library OpenMP.

In addition, we can parallelize other steps of the model. Propagation of the signal field array can be performed independently for each time slice of the field. Similarly, the laser gain calculation, modal content decomposition, and effective area calculation can be performed independently for each of the time slices.

### 19.3. Execution speed considerations

We have both MATLAB and Fortran versions of our model. Both versions use the FFT library FFTW [15]. Our experience is that FFTW is substantially faster than other FFT routines in Fortran.

OpenMP, the shared-memory multiprocessing library and compiler directives, is implemented in the version of Fortran we use, GNU Fortran 4.6.3. Using a desktop computer based on an Intel Core-i7 3770 (Ivy-Bridge) processor with four physical cores, we are able to obtain an excellent speed up. Using four threads instead of one, the time required to run the same fiber setup decreases by a factor of  $\approx 3.2$ .

Another important speedup was obtained by solving the thermal problem and laser gain equations on a coarser  $z$ -grid than the FFT propagation problem. This can dramatically reduce the model run time as well. Care in choosing this grid is important because a grid that is too coarse can reduce the computed gain and increase the instability threshold power.

The run times on our computer lie in the range of 0.25-1.5 hour/m depending mostly on the  $z$  step size and the number of harmonics included in the Green's function. Larger cores use larger  $z$  steps, and near-threshold runs require only a single harmonic, permitting times near 0.25 hour/m.

## 20. Approximations of model

All numerical models make judicious approximations. A brief list of ours follows:

- Single  $\lambda$  pump with single absorption and emission cross sections
- Pump power is uniformly distributed across the pump cladding
- All signal light is identically polarized
- Steady-periodic heating is required for application of Green's function
- Fixed period  $\Upsilon$ , which allows only signal frequency offsets  $1/\Upsilon \times (0, \pm 1, \pm 2, \dots)$
- Thermal boundary condition is fixed temperature on square boundary
- Thermal boundary size approximately three times core diameter
- Heat equation solved in two dimensions (no longitudinal heat flow)
- Thermal properties assumed uniform and isotropic
- Temperature dependence of cross-sections,  $dn/dT$ , and  $\tau$  not included
- No refractive index dependence on  $n_u$
- Signal bandwidth  $< 100$  GHz
- Low contrast refractive index profile, *e.g.* no air-holes as in PCF
- Upper state population  $n_u$  follows  $I_s$  instantaneously (steady-state expression)

## 21. Attributes of model

Attributes of our model include:

- Highly numeric - general and simple to add additional physical effects
- Model a variety of refractive index, linear absorption, and doping profiles
- Steady-periodic eliminates long integration times before steady state
- Steady-periodic model produces well defined thresholds
- The ADI method can be used to study transient behavior if desired
- All transverse modes are automatically included
- Thermal lensing automatically included
- Comparatively short run times and minimal memory requirements
- Variety of thermal boundary conditions possible using Green's functions
- Green's function method offers large speedup using multiple processors

## Acknowledgments

This work partially supported under funding from the Air Force Research Laboratory Directed Energy Directorate.