Improved Nd doped silica fiber for E-band amplification

Leily Kiani, Paul Pax, Derrek Reggie Drachenberg, Jay Dawson, Charles Boley, Cody Mart, Victor Khitrov, Charles Yu, Robert Crist, Matthew Cook, Nick Schenkel, Michael Runkel, Michael Messerly
Lawrence Livermore National Laboratory, Livermore, California 94550, USA
kiani2@llnl.gov

Abstract: Building on previous work, we have designed a Nd doped fiber for E-band amplification. Modeling results indicate a fiber design that is applicable to telecom amplifiers.

1. Introduction

Future optical networks will need to scale capacity in a multitude of approaches to accommodate increased demand [1]. The full network includes metro, long haul, and subsea links. Current operations in the long-haul links are typically in a bandwidth compatible with in-line Erbium doped fiber amplifiers (EDFAs). Alternative in-line amplifier technologies that fill in the available but unused fiber transmission spectrum could enable capacity scaling without the need to install new transmission fibers. Raman fiber amplifiers and Bismuth fiber amplifiers have been developed for amplification at telecom wavelengths, however performance of such laser sources falls short compared to Er-doped fibers [2,3].

A focus of our recent work has been to promote lasing on rare-earth transitions that have previously been inaccessible to laser action because of competition from stronger lasing transitions in the same rare-earth element. The technique relies on an embedded wavelength selective microstructure that sheds competitive emission from the waveguide core. This technique applied to Nd-doped silica fibers can be used to promote E-band (1360 to 1460 nm) amplification [4,5]. Neodymium has two IR transitions other than the well-known transition at 1060 nm, the $^4F_{3/2}$ to $^4I_{9/2}$ that produces light near 900 nm, and the $^4F_{3/2}$ to $^4I_{13/2}$ that produces light near 1400 nm. We have applied the wavelength selective filter to suppress both 1060 nm and 920 nm light to allow amplification near 1400 nm. In a first demonstration of a Nd doped fiber for telecom applications, the fiber design was such that it achieved a mode field diameter of 10.5 µm and an outer diameter of 125 µm, closely resembling a standard telecom fiber [5]. Importantly, the design of the first fiber had a core index matched to silica and the core confinement was generated by a photonic crystal lattice of low index elements. The raised core index, an average of 1.9×10^{-3} higher than that of fused silica, was reduced by mixing with low index fluorine doped glass which also diluted the rare earth concentration to 40% of its original value. Details can be found in Dawson et al. 2017. The fiber produced >13 dB gain in 14 m of fiber. Gain was demonstrated in an 80 nm span of the unused standard fiber transmission window between 1380 nm and 1460 nm. Improvements identified for a next fiber include development of a design where the doped core is not mixed to reduce it to the index of fused silica to avoid dilution of the Nd dopant and avoid the introduction of contaminants that likely contributed to the relatively high background loss (>0.1 dB/m) in the first attempt.

Here we present modeling results from a microstructure fiber design that addresses the drawbacks of the first fiber. The models are developed with measured data from glass components that will be incorporated into a fabrication of the new fiber. This fabrication effort is planned to proceed before the end of 2019.

2. Methods

In our refined design, the core confinement is formed by a step index region in contrast to the photonic crystal fiber lattices used in the previous fiber [5]. The core index is raised to 0.135 NA with respect to the inner cladding region – that is, the region that immediately neighbors the core. Auxiliary elements surrounding the core are strings of graded-index (GRIN) waveguides, pulled from a preform optimized to produce telecom multimode fibers, with relatively high waveguide dispersion due to their high NA (0.20 to 0.30) and small size. These GRINs are arranged in six groups or "spokes" of eight inclusions, with the spokes arranged along a non-radial line in a hexagonal array shown in figure 1. The six spokes consist of 2 sets of 3 spokes, where the size of the GRINs is slightly different from spoke to spoke. The GRINs support modes of their own, which are designed to be resonant with the fundamental core mode at the wavelength we wish to filter; at resonance, the core mode couples to these inclusions. An outer region, formed by the coating, is raised to be higher than that of the core to ensure coupling from the resonant elements toward an outer reservoir rather than back into the core of the fiber. The overall effect is that the core guidance is lost when the resonance condition is satisfied or nearly satisfied, thus creating a wavelength-selective filter. The 2 different GRIN sizes couple to the two different wavelength ranges, where the smaller GRINS couple to the shorter wavelengths – that is, one set of spokes resonantly couples 920 nm light from the core and the other set resonantly couples 1060 nm light from the core. The model also incorporates the deviation from a step-index profile in the core in the as-received core material which impacts the confinement in the core fundamental mode. The core index profile is modeled as a super-gaussian fit to the measured profile. The doped core region is 9 µm in diameter but considering this deviation in the profile, the effective core diameter of the waveguide is 7.87 µm.

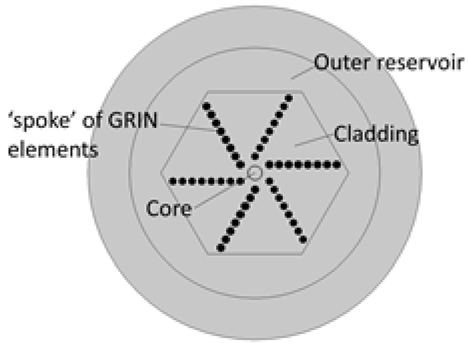

Figure 1. Example of the fiber design geometry. The 8 high index GRIN elements extend out from the core along non-radial lines. The core and GRIN elements are surrounded by the background region forming an all-solid structure. The ends of the GRIN element 'spokes' are located close to the acrylate coating that serves as a reservoir for the outcoupled light.

We model the structure and waveguide losses via a commercial Finite Element Method based mode solver (COMSOL). Figure 1 shows a schematic of the design with GRIN elements and outer reservoir formed by the coating. Beyond the reservoir is an artificial structure, a ring of absorbing material, used to characterize the resonant loss from the core mode. In the actual fiber, there may or may not be dissipation in the reservoir: light that makes its way from the core to the reservoir will not return on the length scales of interest, due to the mode coupling in the large mode volume and high background losses in the reservoir. In the model we introduce dissipation to avoid having to explicitly track the modal population of the reservoir.

3. Results and Discussion

The mode solver produces the field maps of waveguide modes over various wavelengths. Shown in figure 2 are intensity maps for three different wavelengths. For the wavelengths in the filtered bands, 950nm and 1050 nm, it is evident that the LP01 mode in the core couples to the LP11 mode in the GRIN elements. Furthermore, the 950 nm light couples to the smaller GRIN spokes and the 1050 nm light to the larger GRIN spokes.

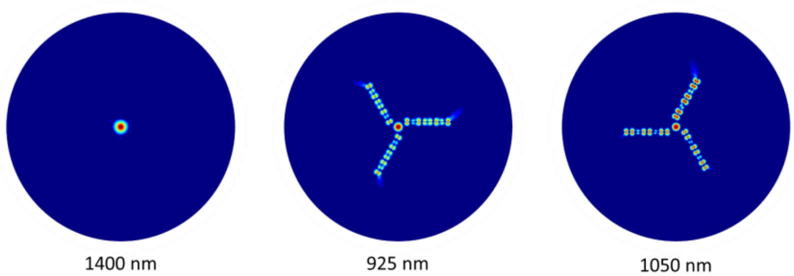

Figure 2. Log intensity maps of the lowest loss core modes for three different wavelengths. Images show values over 3 orders of magnitude.

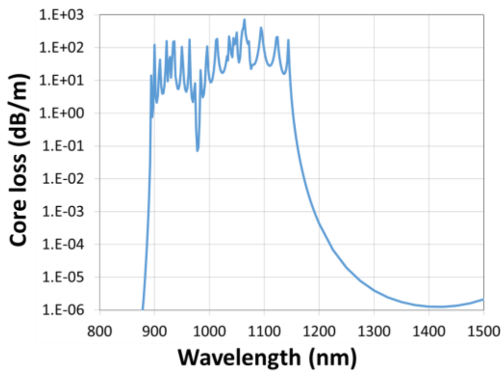

Figure 3. Calculated losses from COMSOL modeling showing loss exceeding 10 dB/m in the range of competitive transitions at 0.9 µm and 1.1 µm.

Figure 3 shows the calculated waveguide losses over the range between the pump at 808 nm and the signal at 1400 nm. Modeling results indicate that gain can be suppressed for both competitive transitions at 0.9 µm and 1.1 µm while maintaining low losses at the pump and signal wavelengths. Note that the fiber loss outside of the filter band will be higher than shown in this plot as its limit will be dominated by Rayleigh scattering.

In summary, we have designed a new Nd doped fiber with reduced mode field diameter to achieve high inversion over short lengths and thus reduce the pump power needed to reach 30 dB of gain, a specific technical goal for telecommunications applications. The reduced core size and increased NA in this fiber reduces the mode field diameter by 25% compared to the previous fiber. An amplifier based on this fiber pumped with commercially available fiber-pigtailed 808 nm is expected to produce 20-30 dB of E-band amplification in roughly 10 m of fiber. We intend to fabricate this fiber design late 2019.

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4. References

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