High power fiber lasers and amplifiers utilizing ytterbium (Yb)-doped fibers have been extensively studied in the past few decades and a phenomenal increase in the peak as well as average power levels have been demonstrated. The primary reasons for such widespread interest are the inherent advantages of a fiber-based medium such as excellent beam quality, relative ease of thermal management as well as small footprint. Owing to the low quantum defect of Yb-doped in silica, the gain medium utilizing the Yb-ion is invariably the choice for applications which require high intensity and high-power sources. However, the power scaling of such fiber lasers are challenged by several factors including fiber nonlinearities, thermal mode instability and self-pulsing. The nonlinearity issue is typically addressed by increasing the mode effective area in large-mode area (LMA) fibers and reducing the length of the active fiber in a master-oscillator power amplifier configuration. Similarly, self-pulsing and pulse distortion due to gain saturation may be avoided by amplifying the signal using multiple stages.

The large-mode area (LMA) double-clad fibers facilitate high-power multimode diode pumping and single-mode (or few-mode) operation, the latter being achieved by reduction in the numerical aperture (NA) of the core. However, the LMA fibers have been reported to exhibit an instability in the transverse modes of the fiber beyond a certain threshold average power, which has been attributed to thermal effects. In some cases, an initially single mode fiber has been said to exhibit guidance of the first higher order mode after a certain threshold of signal power is achieved. From literature, it is known that this instability threshold depends on the average power and not on the peak power of the signal and the instability or exchange in power among the transverse modes does not reflect as a power fluctuation at the output.

The key objective of this work is to design a testbed wherein the thermal mode instability (TMI) can be investigated in a controlled manner without triggering other nonlinear effects in the amplifier. This is achieved by modulating the seed laser radiation with different duty cycles, thereby varying the thermal load in the final amplifier. An acousto-optic modulator (AOM) can be used to externally modulate the seed for this purpose which gives more stable output and freedom for a larger range of pulse-widths and repetition rates as compared to direct modulation of the seed. The present work is towards the design of a multi-stage MOPA with a high average power to achieve power levels at which the thermal mode instability threshold have been reported before. The design of the high power amplifier is presented which includes four amplification stages where the parameters at each stage is optimised using RP-Fiber Power software such that the output of the final stage is > 500W. Based on this design, the preliminary experimental results are also presented here and these results are compared with that expected from the design.
Simulation Design for Multi-stage amplification

The multi-stage MOPA design constitutes of a seed source (FWHM linewidth < 0.1 nm) followed by four amplification stages as shown in Fig. 1. An acousto-optic modulator after the seed source is for facilitating external modulation in future which can thus vary the heat load (which is not discussed in the present work). The operation of the MOPA in continuous-wave mode is considered here. The simulations have been done so as to obtain sufficient gain at each stage, with the target of achieving >500 W at the final stage output.

**FA1 stage:** The input signal power of 35 mW and pump power of 250 mW (at 976 nm) are used to optimise the FA1 stage active fiber length (6/125 µm Yb-doped single-clad fiber). For 1.5 m length of the active fiber, the ASE at 1030 nm is suppressed and the output signal power is estimated to be 218 mW at the output of the doped-fiber.

![Fig. 1 Multi-stage amplifier design; FA: Fiber amplifier, AOM: acousto-optic modulator, CPS: cladding-pump stripper](image)

**Fig. 1 Simulation results for pump, signal, forward ASE and backward ASE power as a function of active length for (a) FA1 (b) FA2 (c) FA3 and (d) FA4 amplification stage**
The variation of the pump, signal, forward and backward ASE powers are as shown in Fig. 2(a). The gain expected at this stage is 7.9 dB.

**FA2 stage:** The insertion loss of the components (such as the combiners, isolators and cladding pump strippers) are incorporated from the specification sheets of the components to be used in the experiments in the calculation of input pump/signal powers at every stage. After incorporating the insertion loss of isolator and the combiner at the signal wavelength, the input power at 10/130 µm Yb-doped double-clad fiber (DCF) is estimated to be 116 mW. A laser diode operating at 915 nm is used for pumping the doped fiber in this stage. The pump, signal and ASE power variations with length are shown in Fig. 2(b). For a pump power of 6W, the active fiber length for the optimum output was 5 m from the simulation. For this length, the output signal power obtained from simulation is 3.42 W and the gain is 14.7 dB.

**FA3 stage:** The signal power input to the active fiber at this stage (15/130µm LMA Yb-doped DCF) is estimated to be ~ 2.08 W after accounting for the insertion losses of the components in between. The total pump power that can be launched is about 80W, targeting ~ 15dB gain from this stage. For an optimum length of 3.3m, at the maximum pump power, the output signal power obtained from the simulation is ~ 72 W. The power variations are shown in Fig. 2(c).

**FA4 stage:** The signal input to the active fiber at this stage (25/250µm LMA Yb-doped DCF) is estimated to be ~ 30 W incorporating the insertion losses. The active fiber at this stage is a LMA few-mode fiber which is chosen to lower the threshold of TMI in the experiments, thus facilitating its study. The total pump power to be launched at this stage is about 680 W. For an active fiber length of 4 m considering attenuation of 10 dB/km, the output signal power obtained from the simulation is ~ 635 W with a gain of about 13.2 dB. The power variations are shown in Fig. 2(d).

These simulations provided the estimate of lengths and pump powers necessary at each stage. The experiments have then been carried out with parameters close to these estimates.

**Experimental Results and Discussion**

The results from the experiments carried out till now have been presented here and compared with simulation results from RP-fiber power with the same input parameters as obtained experimentally at each stage. A total pump power of 256 mW at 976 nm is available at the FA1 stage. The signal power fed into the 1.5 m FA1 active fiber (single-clad, absorption at 976 nm: 250 dB/m) is ~ 36 mW. The variation of the output signal power with the pump power is as shown in Fig. 3(a).

![Fig. 3 Experimental results for output signal power variation with pump for (a) FA1 (ii) FA2 and (iii) FA3 stage](image-url)
The maximum signal output obtained at this stage is 182 mW which is less than that expected from simulation as shown in the same figure. Thus, a gain of 7.04 dB is obtained from the first amplification stage. From the design plan, the gain expected from this stage was 7.90 dB. An isolator is spliced at the output of this stage.

The available signal power at the input of the 5 m length of FA2 active fiber (double-clad, pump absorption at 915 nm: 1.1 dB/m) is ~ 90 mW. The laser diode (915 nm) is used to launch pump power of 6.9W into the inner cladding of the Yd-doped DCF. The output signal power with increasing pump power is as shown in Fig. 3(b) with a maximum signal output power of 3.22 W. A gain of 15.5 dB is obtained from this stage. The available pump power was more than that considered in the design plan and thus the gain obtained from this stage is also higher. With the matched input parameters at this stage, the simulation result is also observed to be close to the experimental values as shown in 3(b). The input signal power to FA3 was about 2.28 W and for a pump power of 31W at 975 nm and active fiber length 3.3 m, signal power of 26W could be achieved at the output. Up to these pump power values, the output has not deviated considerably from the design plan as seen in Fig. 3(c).

Experiments for further scaling the signal in this stage are ongoing but require more caution due to effects like self-pulsing as well as possible thermal issues.

Conclusion
A testbed design has been presented for achieving hundreds of watt of average power towards the study of effects such as thermal mode instability which are currently the limiting factor in further power scaling in fibers lasers (using LMA fibers). The design sets a guideline for the gain to be achieved at every amplification stage, which is followed by the results from the experiments of multi-stage amplification initiated in order to achieve the desired power levels. The signal levels obtained experimentally are in accordance with the design in the results obtained till now and at the third amplification stage further scaling is subject to efficient cooling mechanism as well as circumventing self-pulsing.

Acknowledgement
The authors would like to acknowledge financial support from AOARD Grant # FA2386-15-1-5044. Yusuf acknowledges DEITY for the Visvesaraya PhD Scholarship. We would also like to acknowledge technical support from Yuvaraj K and Suresh Kumar in carrying out the experiments.

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