# Determination of amplification characteristics in end-pumped solid-state amplifiers

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## ABSTRACT

In this work, we explore the amplification of an end-pumped Nd:YAG crystal rod and propose a new 3D modelling method to study the amplification potential and thermal-induced lensing. We use beam shaping theory to model the pump beam transformation accurately over the length of the crystal. We verify our theoretical approach experimentally using a novel double-pass amplifier configuration for power scaling of a diffraction-limited Gaussian beam. We demonstrate over 95% correlation between our model and the corresponding experiment across the small and high signal amplification regions while preserving the M2 of the input Gaussian beam.

## INTRODUCTION

Master Oscillator Power Amplifier (MOPA) systems have garnered considerable interest to power scale low power seed beams (from the Master Oscillator) to higher powers [1]. To date, the theoretical models describing the characteristics of Nd:YAG, end-pumped systems have been limited to single-pass amplifiers using a two-dimensional model to predict the amplification output and thermal lens effect. Here we present a novel double-pass amplifier system with a supporting analytical model in 3-dimensions, with complete control over the deterministic parameters, such as pump power, beam sizes and gain medium properties.

## THEORY

To simulate the 3D propagation dynamics of the Gaussian and pump beams we use the beam propagation method, where the crystal volume is sliced into many small segments ($S_N$) of length $\Delta z$, as shown in Fig.1. [2]

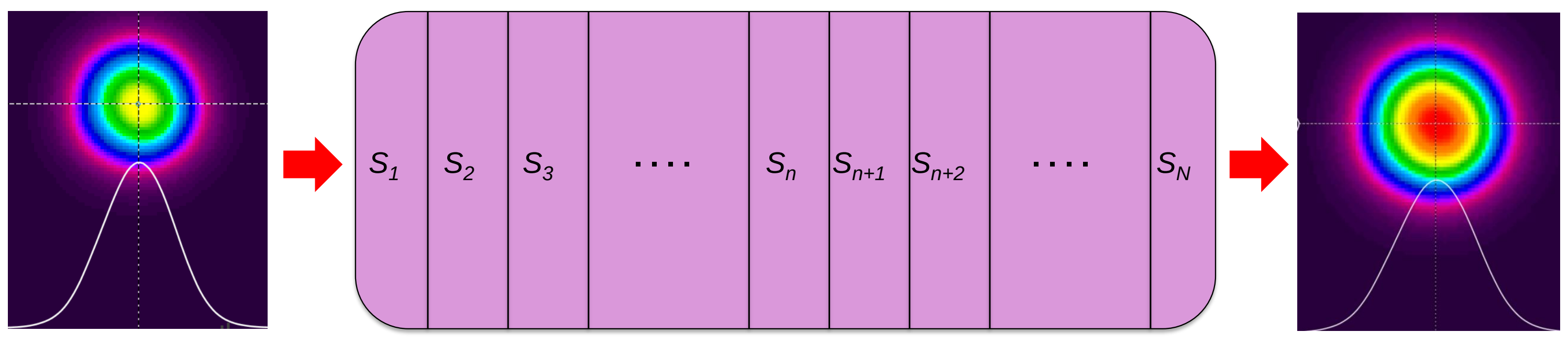


Fig. 1. Schematic of  the crystal volume sliced into equal segments.

At each z-interval, the amplitude and phase of the Gaussian beam are modulated by a gain and change in refractive index term, respectively, to simulate amplification and thermal lensing effects [3]. As shown in Fig. 2, the intensity profile of the pump beam is Flat-top at one end of the crystal but rapidly evolves to a Gaussian profile at the opposite end. To simulate this, we modelled the pump beam using a Gaussian to Flat-top beam transformation so that the pump beam was Flat-top and Gaussian at opposite ends of the crystal, as it appears experimentally.

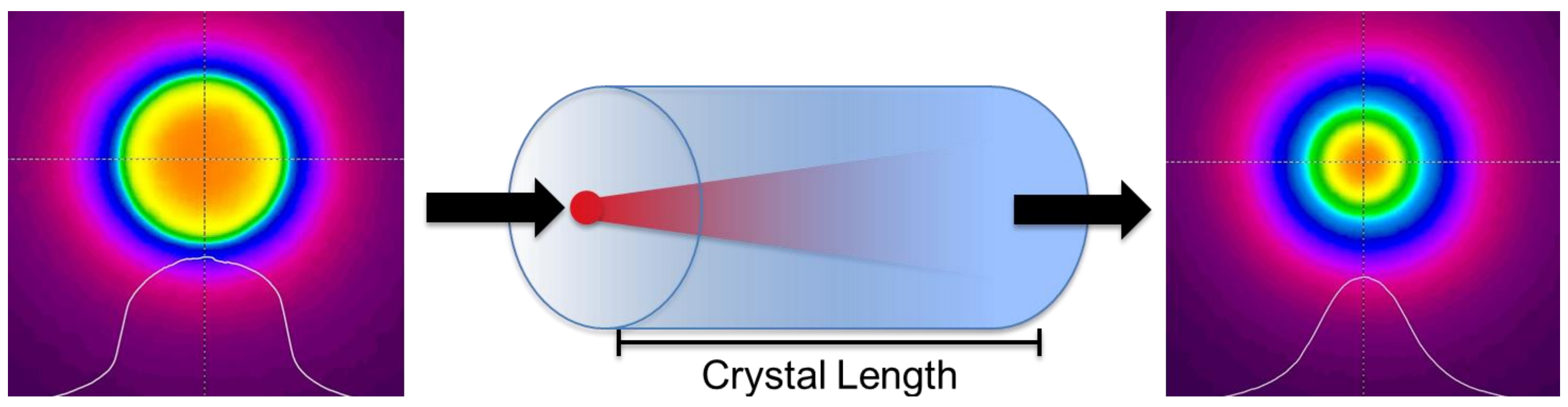


Fig. 2. Pump beam evolution from Flat-top to Gaussian over the crystal length.

The absorption of the Gaussian to Flat-top pump beam, shown in Fig. 3, produces a dynamic thermal gradient inside the crystal, leading to variations in the refractive index that are unique for each z-interval.

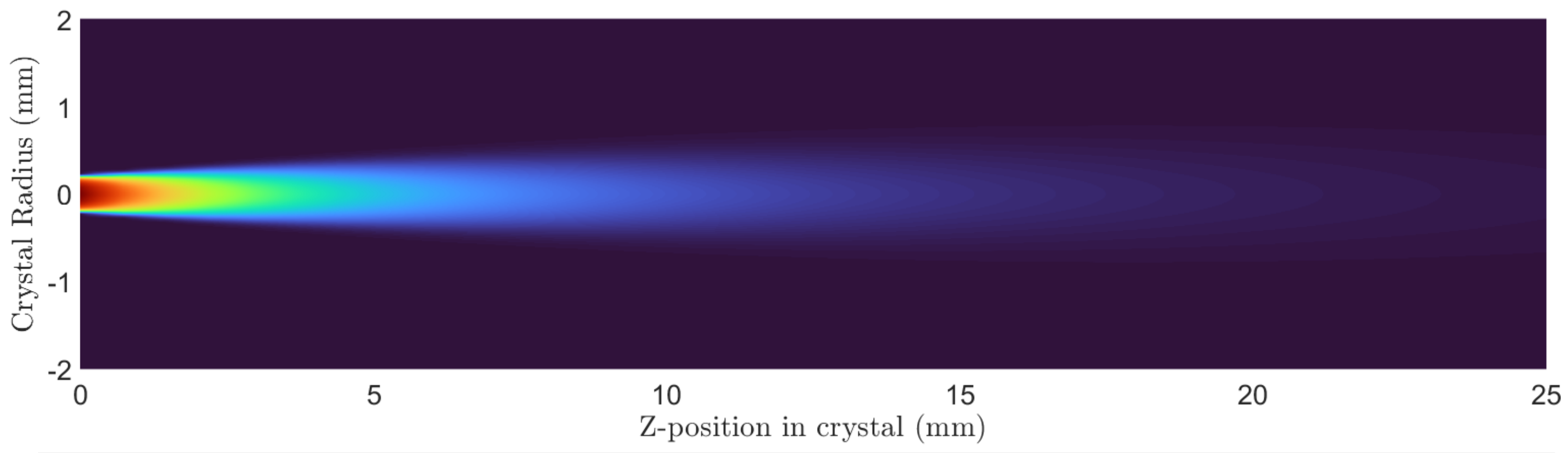


Fig. 3. 2D absorption of Gaussian to Flat-top pump beam shaping

## EXPERIMENT

In Fig. 4 below, we present the schematic of a novel double-pass amplifier configuration. Here, horizontally polarized light from the master oscillator enters the amplifier through the first polarizing beam splitter (PBS 1) and is amplified as it passed through the end-pumped crystal. The amplified output then passes through a half-wave plate so that the polarization of the beam becomes vertical. Allowing the beam to reflect off both PBS's to pass through the pumped crystal for a second time. The double-pass amplified output is then converted back to horizontally polarized light through the half-wave plate and coupled out of the system at PBS 2.

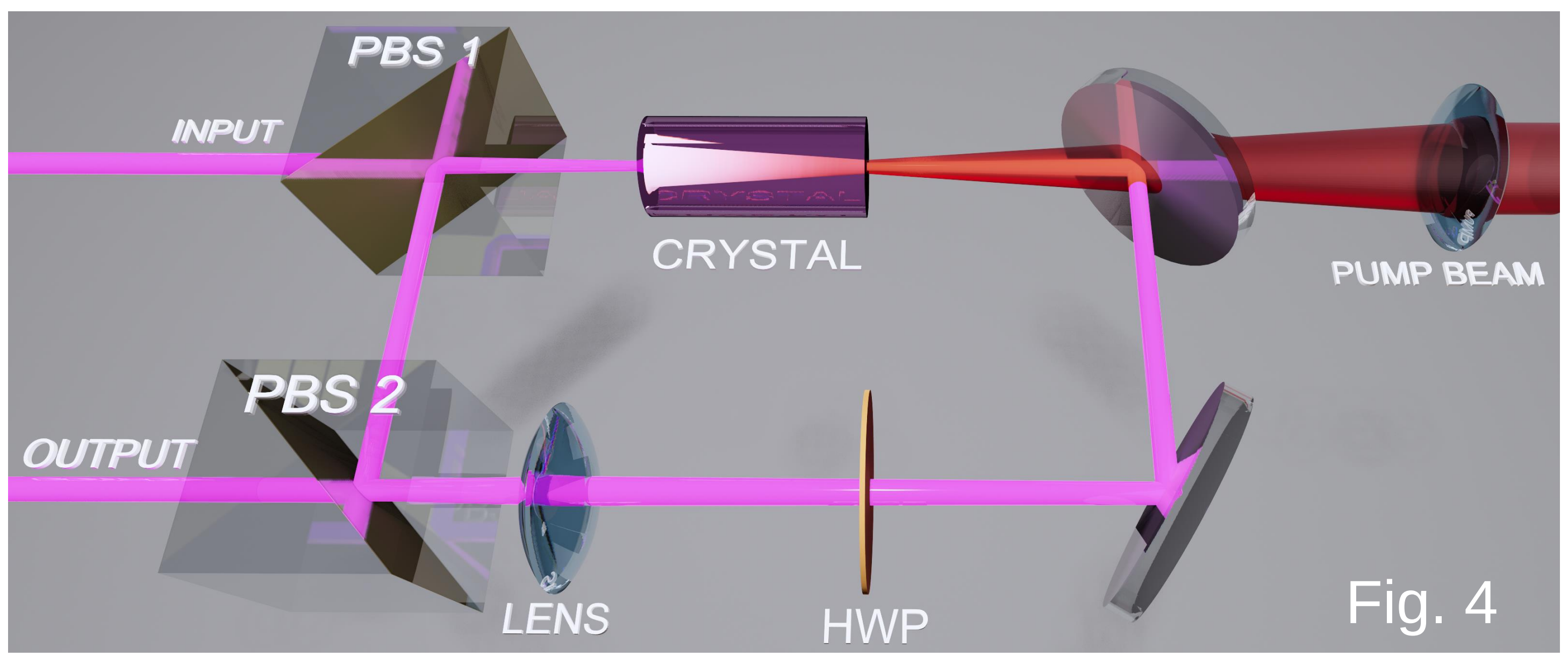
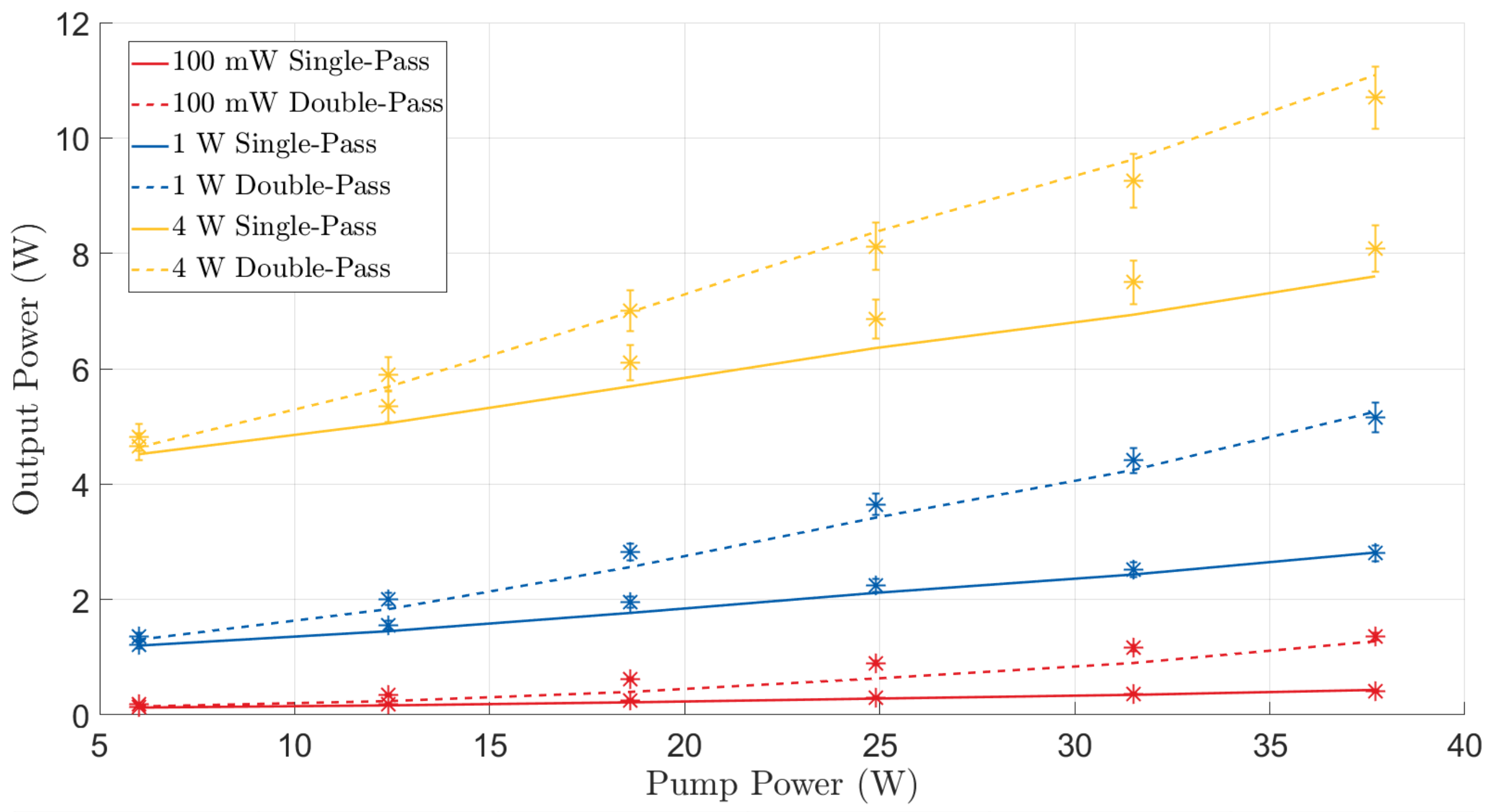


Fig. 4

## RESULTS & DISCUSSION

As shown in Fig. 5, the experimental data points show good agreement with the numerical predictions of our model. Table 1 highlights the results of the experiment. In the gain multiplier column, the 100mW, 1W and 4W beams achieved a 14x, 5x and 2.7x amplification factor, respectively. This is in good agreement with the literature and shows the transition between the exponential and linear gain regions due to the increasing saturation intensities of the input seed. The M2 for all the seed powers in single and double-pass amplification was preserved and remained diffraction-limited, indicative that the thermal effects were not severe or detrimental to the beam quality at the various pump powers ranging from 6W to 37W.



| Input Power (W) | Single-Pass (W) | Double-Pass (W) | Gain multiplier | $M^2$ Single-Pass | $M^2$ Double-Pass |
|---|---|---|---|---|---|
| 0.100 | 0.415 | 1.39 | 14 | 1.17 | 1.17 |
| 1 | 2.8 | 5.15 | 5.15 | 1.18 | 1.19 |
| 4 | 8.08 | 10.7 | 2.67 | 1.16 | 1.13 |

Fig. 5. (top) Theoretical and experimental results for single-pass (solid lines) and double-pass (dashed lines) & Table 1 (bottom) highlighting the results.

In conclusion, we have successfully demonstrated a proof of concept of a novel double-pass amplifier system, with an accurate supporting analytical model. The model is able to predict the amplification across various seed and pump powers in both single and double pass operations.

## REFERENCES

[1] W. Koechner. Solid-State Laser Engineering, pages 156–209. Springer New York, NY (2005).
[2] Z. Xiang,et al. Beam quality improvement by gain guiding effect in end-pumped Nd:YVO_4 laser amplifiers, Optics Express (2011)
[3] D. Bričkus, et al. Modeling of thermal lensing in a [1 1 1]-cut Nd:YAG rod with temperature-dependent parameters and different pumping profiles, Laser Physics (2017).