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# High-order mode excitation in end-pumped solid-state lasers around cavity degeneracy lengths

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The excitation of transverse modes in a solid-state laser has been a subject of great interest for a long time [1], because some high-order modes possess angular momentum or low divergence, and are interesting for applications such as optical tweezers, particle trapping, and microscopy. Recently, Ince-Gaussian (IG) solutions to the paraxial wave equation have attracted considerable attention. IG modes have been observed [2] and also numerically studied [3] in stable resonators. These observations occurred near a degeneracy length of the cavity. High-order Laguerre-Gaussian (LG) modes can also be excited in an end-pumped solid-state laser [4] and we note that it also happens in the vicinity of a degeneracy length. In this paper, we give a comprehensive study of high-order modes in solid-state lasers, including the crucial role of the pump-induced thermal profile.

Our experimental set-up consists first in a simple diode end-pumped Nd:YAG laser using a plano-concave resonator. We observe that high-order IG modes are emitted only when the resonator length is near a degeneracy length, here  $R_c/2$ . Also, while the far-field looks very similar to IG modes, a close inspection shows that the emitted modes are not shape-invariant, leading us to conclude that these modes are not pure IG modes (see Fig. 1). Simulations based on the Fox-Li method yield comparable profiles.

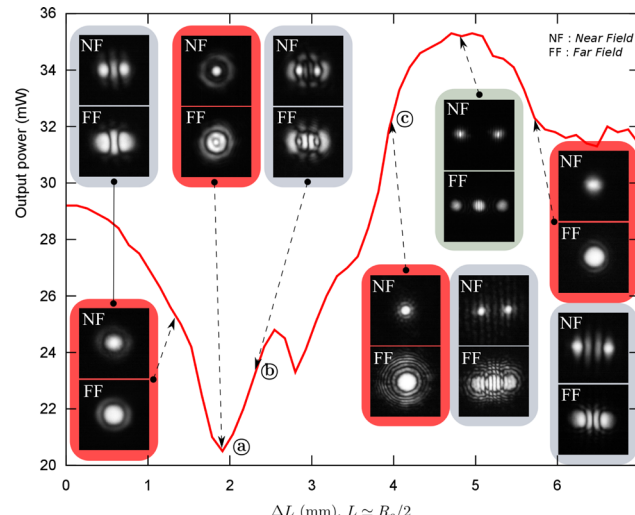


Fig. 1: Experimental Nd:YAG laser power evolution (red curve) across the  $L=R_c/2$  degeneracy length. Insets: red boxes, pump aligned; grey boxes, pump misaligned. Quasi-LG and quasi-IG modes appear in (a) and (b), respectively. Geometric modes (c) appear close to the maximum of the output power curve which corresponds to the true degeneracy.

According to our analysis based on a gain-matching integral, using a Gaussian pump beam, pure high-order modes cannot be excited. Only non-invariant mode superpositions, that we call quasi-IG (or quasi-LG) modes can be emitted. We find that the excitation of such modes requires being near a degeneracy length [5]. Our Fox-Li simulation includes the thermal profile inside the active medium, and it is interesting to note that an effective Gaussian phase profile has to be taken into account in order to reproduce the asymmetric shape of Fig. 1. We prove the crucial role of this phase profile by making the same experiment but with a Nd:YLF crystal, that bears a negative  $dn/dT$ . In this case, the asymmetry is reversed around the degeneracy length, and quasi-IG or quasi-LG modes are observed at lengths longer than the perfect degeneracy length, contrary to the Nd:YAG case.

The theoretical conclusions agree well with our experimental results, and could help to design solid-state lasers for applications based on high-order modes.

## References

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