High-order mode selection in Yb:YAG ceramic laser

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Yb-doped gain media have been investigated for decades and have recently gained importance as a vital option in the construction of both high-power and ultra-short pulse lasers. Yb-doped gain medium used in developing diode-pumped terawatt facilities has shown the importance of further studies on this active medium. Very high optical efficiency, diffraction-limited beam quality, and output powers of more than 1 kW have been achieved with ytterbium-doped double-clad fiber lasers and amplifiers. Thin-disk lasers, which most often work with Yb:YAG crystals, can also generate well above 1 kW diffraction-limited output with high beam quality, or even higher powers with non-diffraction-limited beam quality. Various Yb-doped gain media have been used in mode-locked lasers for the generation of femtosecond pulses; the by far highest average output powers of 80 W have been obtained with a passively mode-locked thin-disk Yb:YAG laser. For passive mode locking, problems can arise in the form of Q-switching instabilities. This tendency is a consequence of the relatively small laser cross sections of ytterbium-doped media. Therefore, some of the broadband ytterbium-doped gain media are not very suitable for passively mode-locked lasers, particularly at high power levels, but can still be very useful in regenerative amplifiers. Relatively large cross sections are found for tungstate crystals. Some ytterbium-doped crystals have a fairly broad amplification bandwidth, but the emission curve is not very smooth; it exhibits several maxima. In such cases, wide wavelength tunability may still be achieved, but the realization of very short pulses with mode locking is difficult.

On the other hand, in recent years, considerable interest has been shown in the generation of laser beams containing phase singularities. These beams are best described in terms of Laguerre-Gaussian modes which have an azimuthal phase term and possess a well defined orbital angular momentum per photon. The identification of light beams with a well defined orbital angular momentum, which is distinct from the spin component, has led to a number of exciting studies. These include the transfer of the orbital angular momentum to macroscopic objects, the mode transformation upon nonlinear frequency doubling, and the interaction of these beams with atomic systems. The methods to generate such beams have been widely studied in detail and these have involved either using phase elements in Nd-doped lasers or extra-cavity diffraction plates. While Yb- has been proving itself as a potential gain medium, there are not many works that have tried to bring them into the scene as a valuable source for generating high-order circular modes. With high-order modes gaining importance for their wide range of applications especially in the optical toolbox for trapping and tweezing; it is important that we study the role Yb-doped lasers play in generating such modes. Using an intra-cavity lens inside an Yb:YAG ceramic laser cavity, we have succeeded in generating the highest mode orders in Laguerre-Gauss beams experimentally demonstrated so far. We also generate beams in doughnut-like and Bessel-like profiles that exhibit near-diffraction free characteristics of their central lobes for over tens of meters. Radial and azimuthal polarized doughnuts of high polarization purity and high-order modes were also generated from Yb:YAG ceramic laser cavity.

This works demonstrates an economical and less complicated laser scheme to generate high-order modes from an Yb:YAG ceramic laser cavity with unique properties and hence varied applications. The intra-cavity mode selecting element is a simple plano-convex glass lens and it has been shown to offer excellent mode selection in scalar Laguerre-Gauss modes, modes with near-diffraction free characteristics, and radial and azimuthally polarized modes from within the Yb:YAG cavity.

The current study bridges two different regimes that have not been brought together so far; and the end-product is a quasi-three level laser system to realize circular mode selection. In case of a laser resonator with intra-cavity lens, the stability conditions of the cavity as defined by ray transfer matrix are enclosed between the focusing and imaging conditions of the lens at the resonator mirrors. In the presence of strong spherical aberration, the focal length of the lens varies continuously from its axis to the periphery and is no more a defined point but a line. When such a lens is placed at focal length distance from the cavity mirror and shifted along the resonator axis to span across the line focus, the cavity conditions provide continuous selection in modes of increasing mode diameter at the output coupler because of the stability condition shifting to rings of increasing radius along the refracting surface of the lens, generating pure hollow scalar Laguerre-Gauss modes of increasing azimuthal orders as high as 28 (order limited only by the diameter of the cavity optics). Generation of the whole lineage of Laguerre-Gauss modes from a single scheme has been reported by the proposed scheme for the first time.

The laser scheme with aberrated intra-cavity lens can also be set up such that the cavity conditions offer stability for both focusing and imaging conditions simultaneously. Coupling of the cavity modes, enhanced by aperture guiding at the gain element and long cavity length, generates beams which exhibit near-diffraction free properties in their central parts (maximum or minimum). The coupling of these two modes in the cavity has also been confirmed experimentally. Near-diffraction free properties associated with central parts of doughnut-like and multi-ring modes are reported. The near-diffraction free properties of these beams (divergence of their central parts 10 times smaller than the diffraction limit that is associated with the mode radius at the output and constant power confined within the center) exist for over 40 m of propagation distance. When the intra-cavity lens in combination with a birefringent crystal (positive or negative birefringence) inside the Yb:YAG ceramic laser cavity, the stability region of the cavity between the imaging and focusing conditions of the lens is split into two regions; one corresponding to the extraordinary ray and the other to the ordinary ray. The splitting of the stability region allows mode selection in azimuthal and radially polarized modes. The transition point from azimuthal to radial polarization as the lens is shifted along the resonator axis was clearly distinguishable when the width of the stability region (enclosed between focusing and imaging conditions) matched the birefringence shift. Azimuthal and radial polarized doughnut modes were generated with high polarization purity. Polarization extinction ratio as high as 100:1 in certain cases have been reported. Propagation factor M^2 was estimated to vary between 2-2.5 (theoretical value of M^2 for doughnut $LG^*_{01} = 2$). Apart from these doughnut modes, new polarization distribution patterns wherein azimuthal and radial polarizations existed together in a single output beam were generated for the first time. When the intra-cavity lens had pronounced spherical aberrations, the cavity offered mode selection in high-order azimuthal and radial polarized modes.

The experimental work has brought into limelight the realization of certain high-order modes which were only theoretically investigated till date. High-order modes have wide applications related to angular momentum transfer, material processing and many more. Near-diffraction free beams generated from the scheme can be seen as a valuable replacement to Bessel beams which has only a very limited propagation distance. Radial and azimuthal polarized modes have extensive applications in the optical toolbox for micromanipulation and some of the new polarization distributions are added tools for realizing new phenomena.