LAGUERRE-GAUSSIAN MODES SELECTION IN DIODE-PUMPED CERAMIC LASERS

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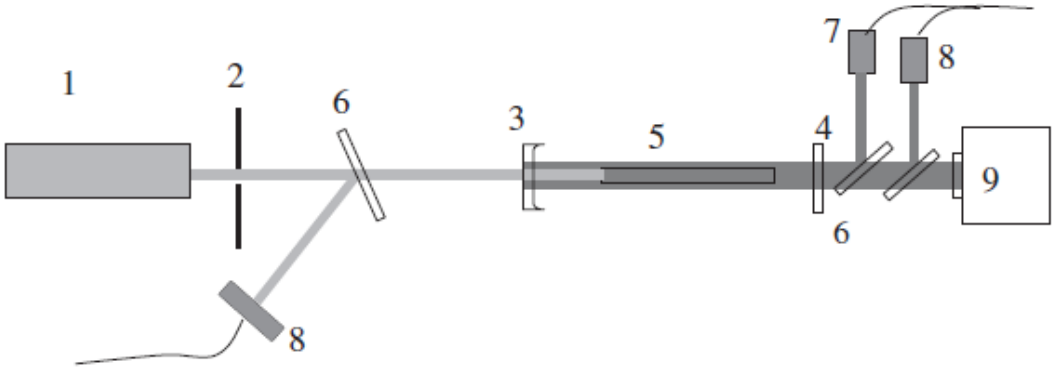
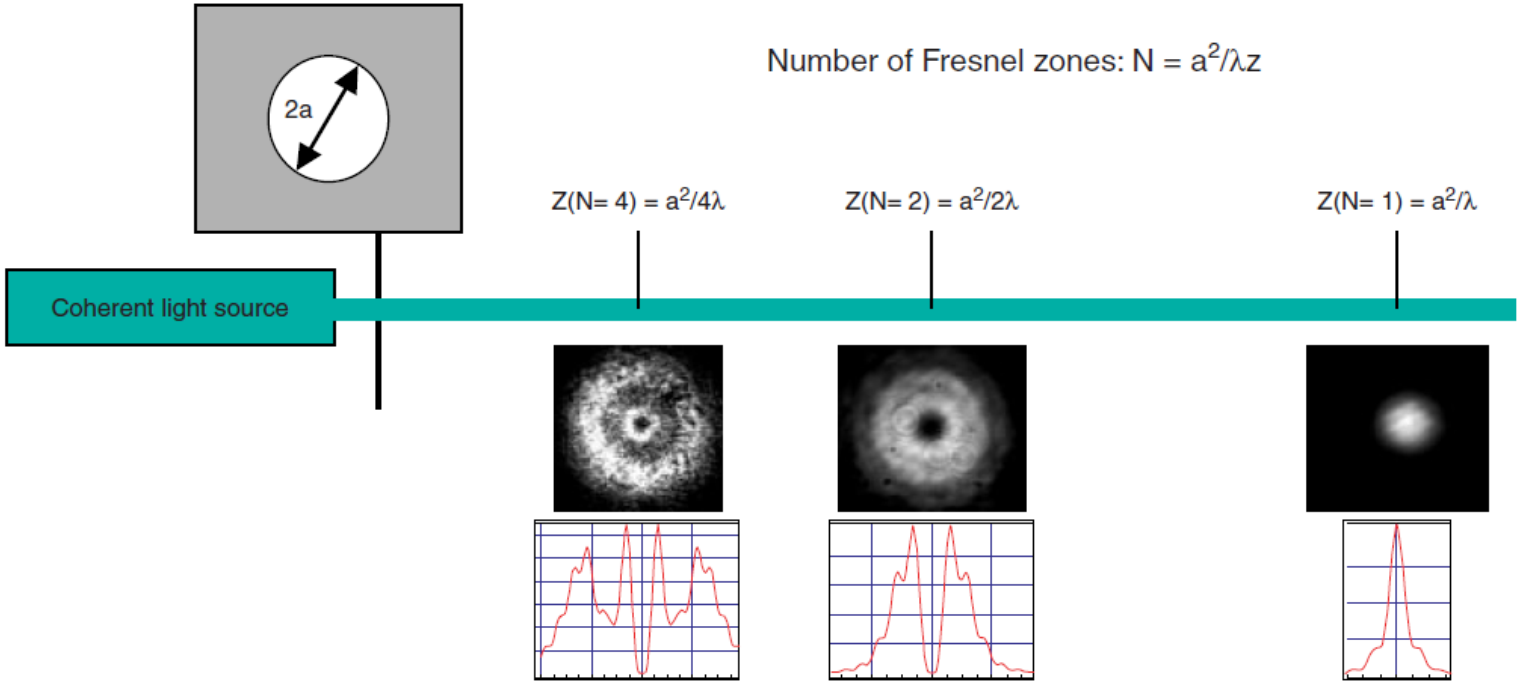
Outline

1. **Introduction**
2. **Laguerre-Gaussian modes classification**
3. **LG scalar modes selection**
4. **LG vector modes selection**
5. **Conclusion**

Diffractive optical pumping of the gain switched Nd:YAG ceramic laser

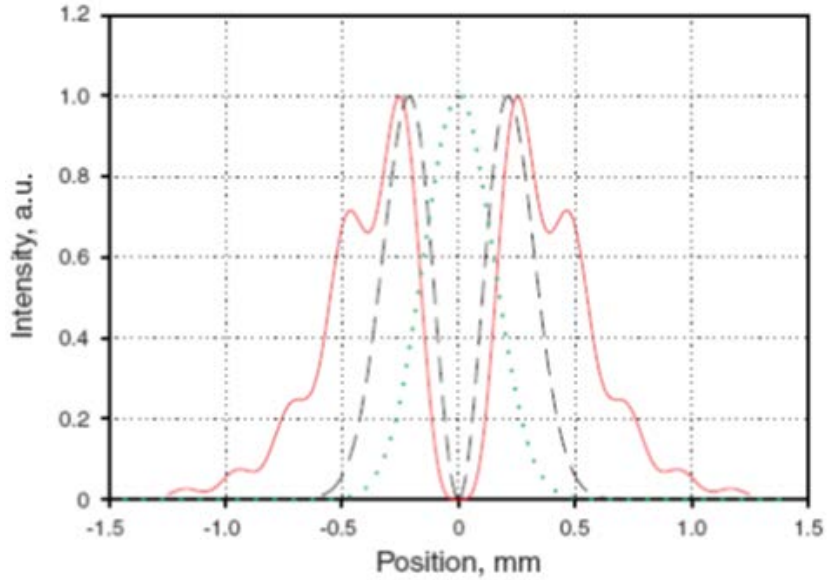


1-frequency-doubled, pulsed (10mJ, 5ns,10Hz) Nd:YAG pump laser; 2-‘‘pumping’’ aperture, d=1-3mm; 3-HR concave mirror; 4-plain mirror, R=98% ; 5-Nd:YAG ceramic rod; 6-beamsplitters; 7-photodetector; 8-powermeter; 9-CCD camera.

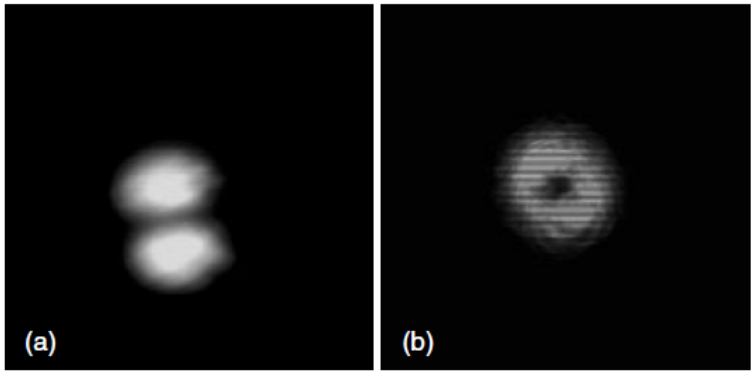


0,53μm pump beam images and intensity profiles for distances corresponding to Fresnel numbers, *N* =1, 2, 4.

LG_{01} and LG_{01}* modes selection in the Nd:YAG ceramic laser by 0,53µm diffractive optical pumping



Calculated profiles of the pump in the 0,6at% Nd:YAG ceramic Ø8x90 mm rod (solid) and that of the LG_{01} (dashed) and LG_{00} (dotted) modes; semi- confocal cavity, length L=25cm, mode waist w=300µm



CCD camera images of LG_{01} (a) and LG_{01}* (b) modes output of the gain switched 1,064µm Nd:YAG ceramic laser (≈100ns, 10Hz, ≈5mW)

Mathematical expressions for scalar LG modes

$$\left(\nabla^2 + k^2\right) E = 0$$

$$E(\vec{r}) = u(\vec{r})\exp(ikz)$$

$$\nabla_\perp{}^2 u = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 u}{\partial \varphi^2}$$

LG_{pm} modes are obtained when the separation of variables is in r, φ and z.

$$u_{pm}(r,\varphi,z) = \sqrt{\frac{2p!}{\pi(1+\delta_{0m})(|m|+p)!}}\left(\sqrt{2}\frac{r}{w(z)}\right)^{|m|} L_p^{|m|}\left(2\frac{r^2}{w(z)^2}\right)\frac{w_0}{w(z)}\exp\left(i\phi_{pm}(z)\right)\exp\left(i\frac{k}{2q(z)}r^2\right)\exp(im\varphi)$$

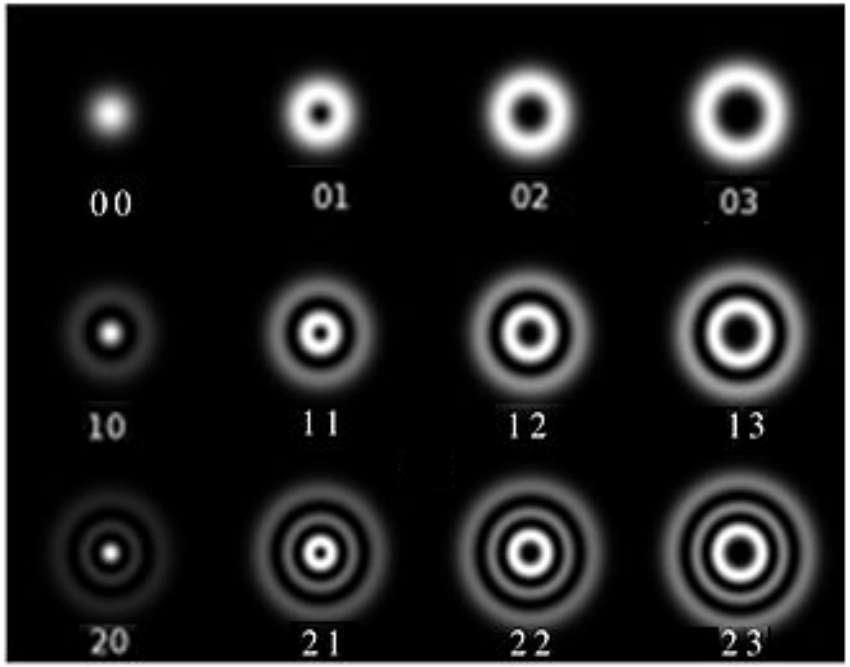
p – radial index, m – azimuthal index; $p \in \{0,1,2,3,...\}$ $m \in \{..., -2, -1, 0, 1, 2, ...\}$

$L_p^{|m|}(x)$ is the Laguerre polynomial, $\phi_{pm}(z) = (2p + |m| + 1)\tan^{-1}(z / z_0)$

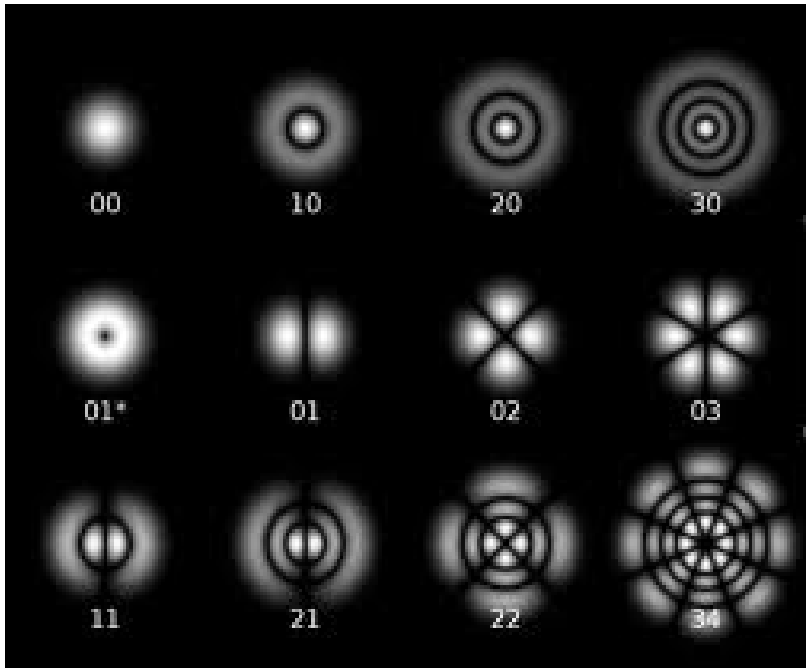
is the Guoy phase shift, $w(z)$ is the beam radius, w_0 is the beam radius at the waist, $z_0 = \frac{\pi w_0{}^2}{\lambda}$

is the Rayleigh range, $q(z) = z - iz_0$ is the complex beam parameter.

Computer simulations of scalar Laguerre-Gaussian modes profiles

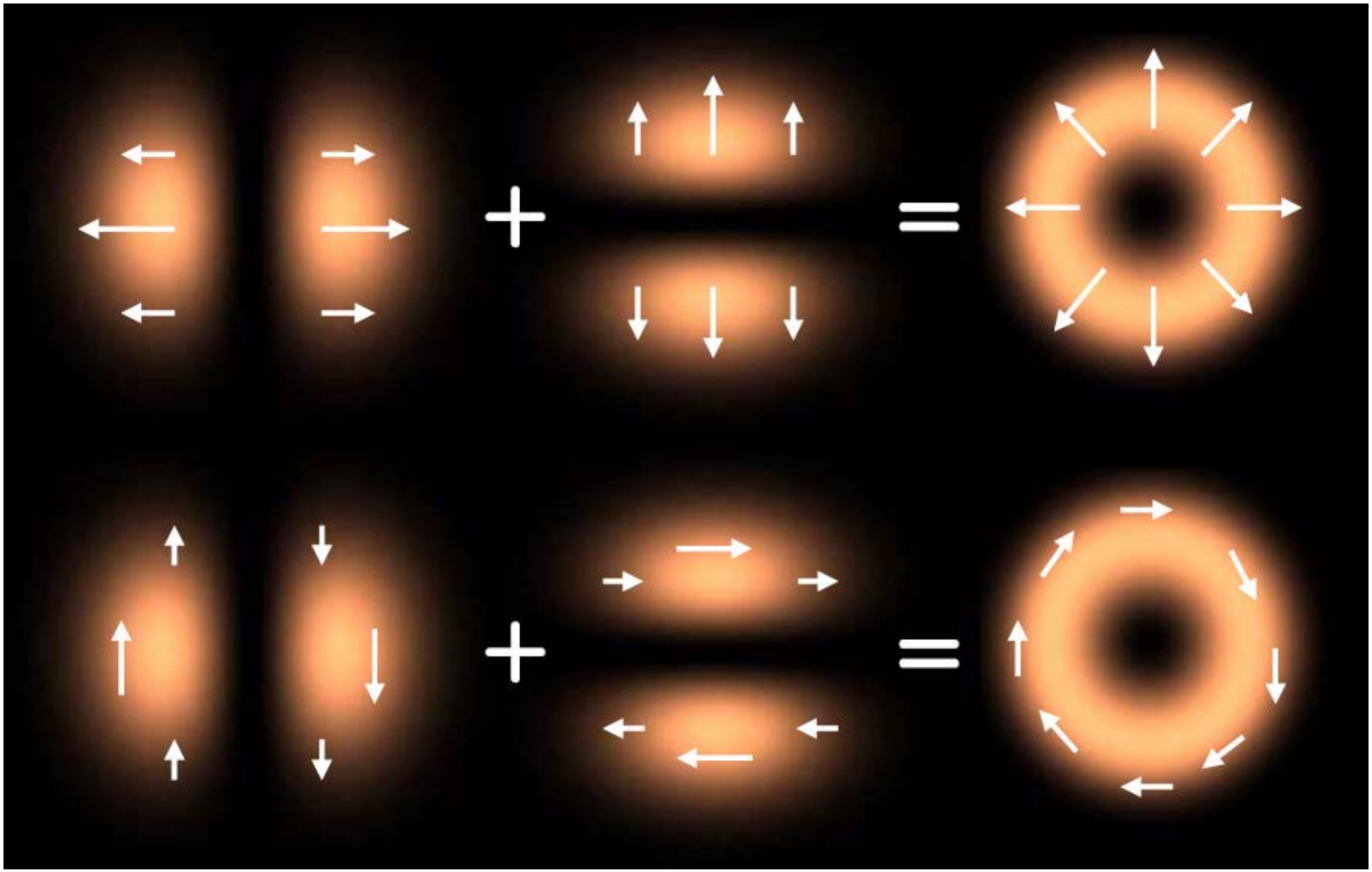


LG_{pm} non-degenerate modes profiles



LG_{pm} degenerate modes profiles

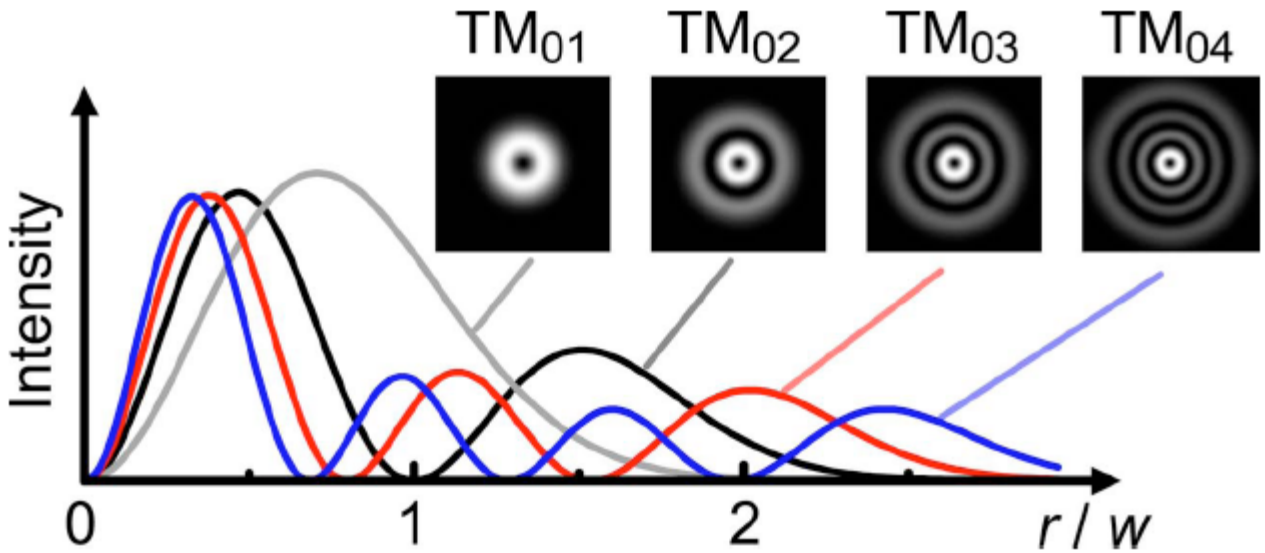
Synthesis of vector LG modes from linearly polarized scalar modes



Formation of radial and azimuthal polarizations using linear superposition of orthogonally polarized scalar modes.

Q. Zhan, Advances in Optics and Photonics **1**, 1–57 (2009)

Computer simulations of vector Laguerre-Gaussian modes profiles



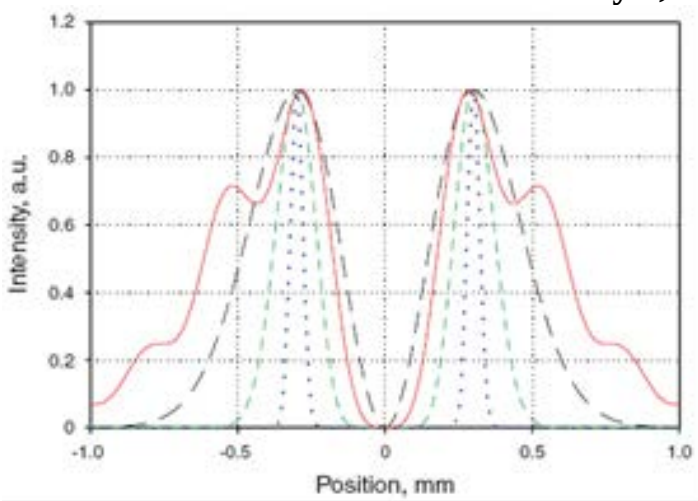
Intensity profiles of radially polarized TM_{0n} modes (n=1,2, 3,4) along the radial direction. The horizontal axis is in units of the Gaussian beam width w.

$$E(r,z) = E_0 \frac{w_0}{w}\left(\frac{\sqrt{2}r}{w}\right) L^1_{n-1}\left(\frac{2r^2}{w^2}\right)\exp\left(-\frac{r^2}{w^2}\right) \times \exp\left(-\frac{ikr^2}{2R} - ikz + i2n\psi\right),$$

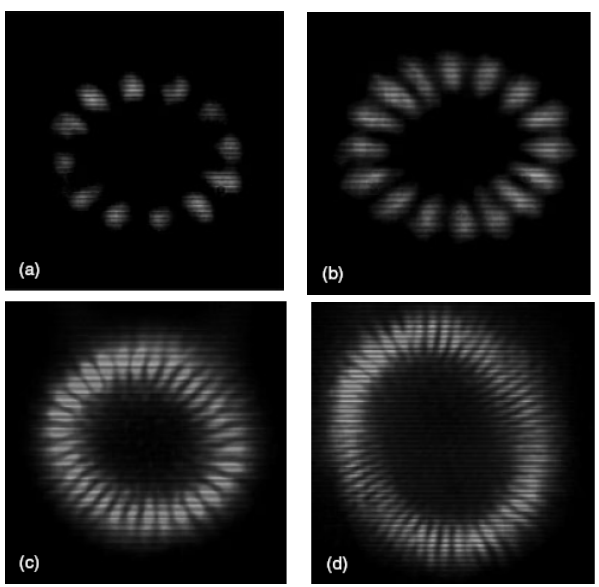
where r is the radius, z is the distance from the beam waist, E_0 is the constant, w_0 is the minimum beam radius at $z=0$, $R=(z_0{}^2+z^2)/z$ is the radius of curvature of the wave front, k is the wave number, $2n\psi$ is the Gouy phase with $\psi=\arctan(z/z_0)$, L is the generalized Laguerre polynomial of order 1 and degree $n-1$, and w is the Gaussian beam width defined as $w=w_0\sqrt{1+(z/z_0)^2}$ with $z_0=kw_0{}^2/2$.

Y. Kozawa and S. Sato J. Opt. Soc. Am. A, Vol. 27, No.3,399 (2010)

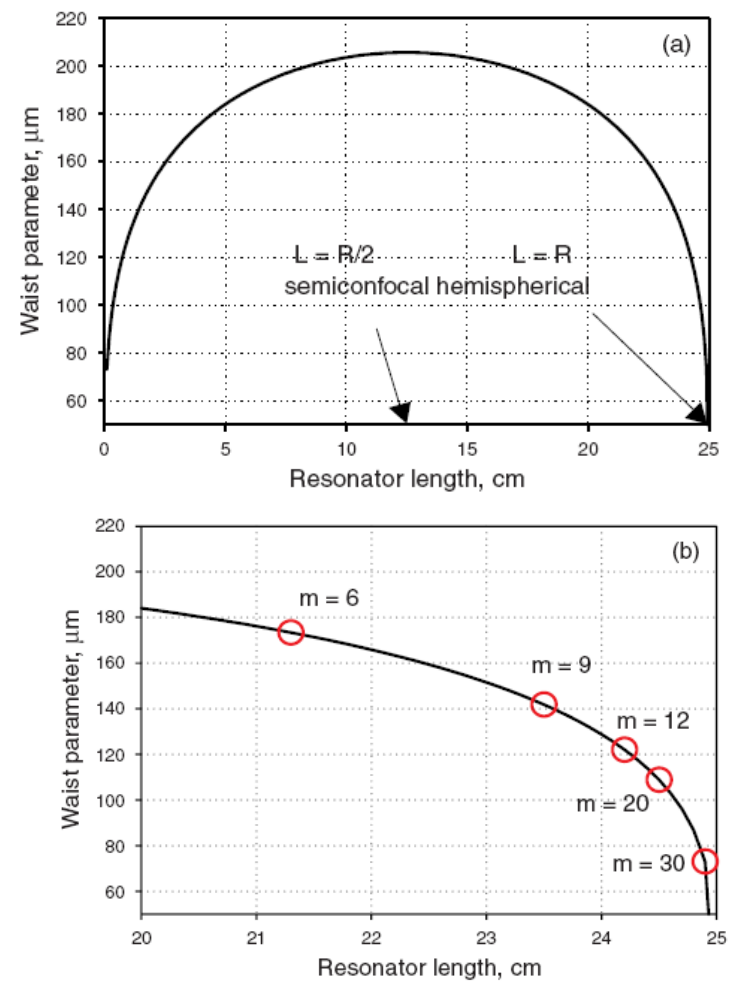
LG_{0m} modes selection in the hemispherical cavity with 4at% doped Ø6x10mm Nd:YAG ceramic rod by 0,53µm pulsed diffractive optical pumping



Calculated profiles: pump (solid); LG_{0m} modes best matching the pump: m = 1, w = 424μm (long dash), m = 5, w = 190μm (short dash), m = 50, w = 60μm (dots)

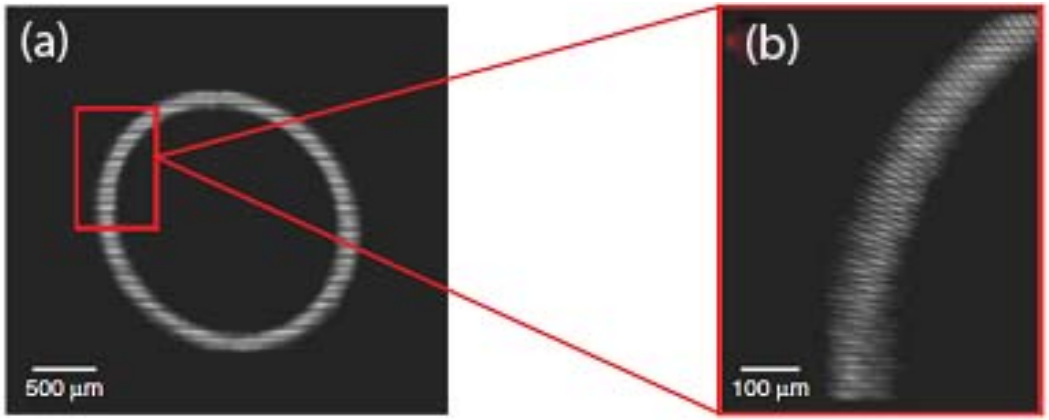


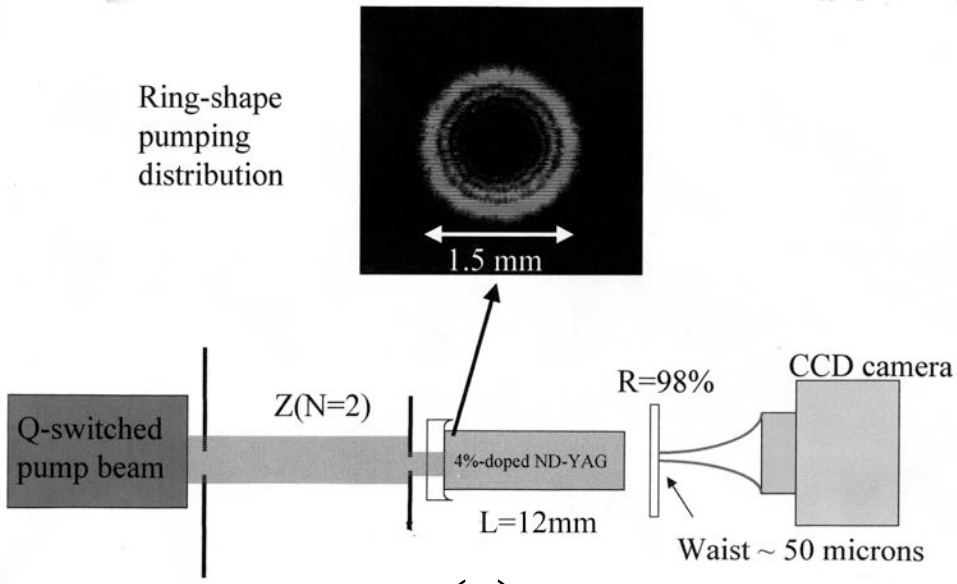
LG_{0m} modes images: m=6(a),8(b),16(c),27(d); ≈500ns,10Hz,1-3mW, λ=1064µm



Waist w parameter on the resonator length dependence-(a); zoom-in the hemispherical region; m-modes orders best matching the pump-(b).

Very-high-order LG_{0m} mode ($m \approx 240$) output of the 0,53μm pumped Nd:YAG ceramic laser

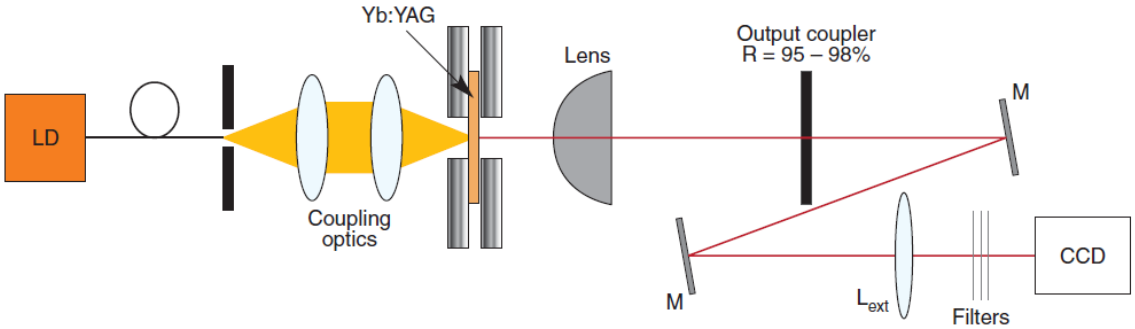




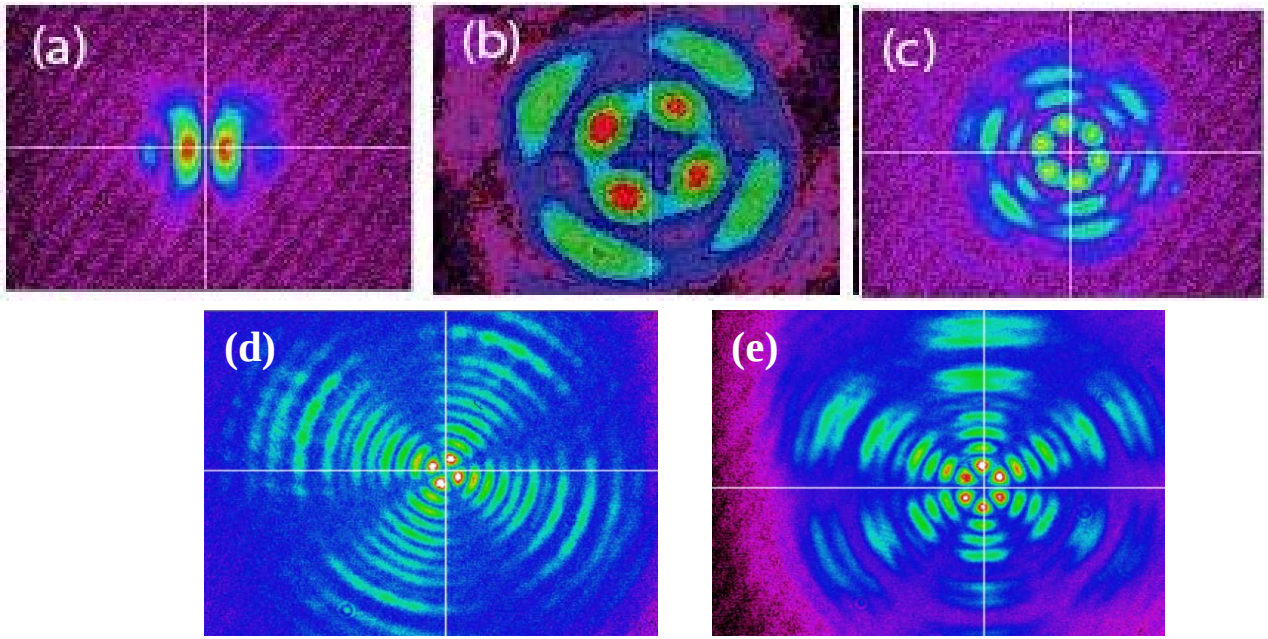
(c)

LG_{0m} mode in a miniature semi-confocal cavity with Ø6x10mm Nd:YAG ceramic rod: (a) CCD camera image of the LG_{0m} mode, $m \approx 240$ ($\theta \approx 0{,}15$ rad, $\lambda = 1{,}064$μm); (b) image of a small part of the output beam circumference; (c) scheme of the experiment.

LG_{pm} modes selection in the LD pumped cw Yb:YAG ceramic laser using an intra-cavity lens with spherical aberration

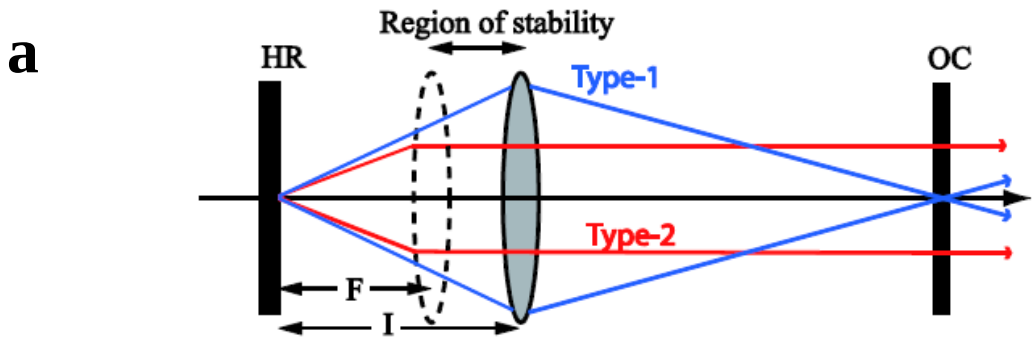


Scheme of the laser on the base of 9,8at% Yb:YAG ceramic 9x11x1,5mm ^{3} plate (with HR coating) in copper cooling slabs; LD pumping at 0,94μm, cavity length, L=80-127cm, f_{ax}=25mm.

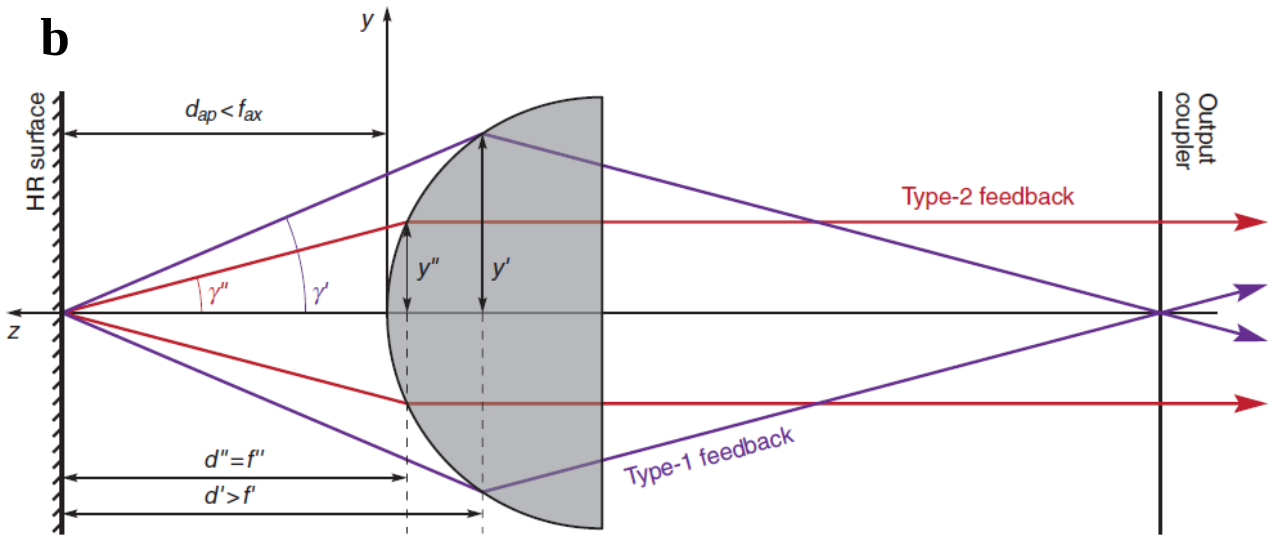


Near-field images of LG_{pm} modes at different shifts of the intra-cavity lens along the resonator axis: a) p=0, m=1; b) p=1, m=2; c) p=2, m=3,(d) p = 11, m =2; (e) p=10, m=3 (10-30mW, θ=0,5-3mrad, λ≈1,03μm).

Ray tracing in a plane-parallel resonator containing:(a)-thin lens, (b)-lens with aberration

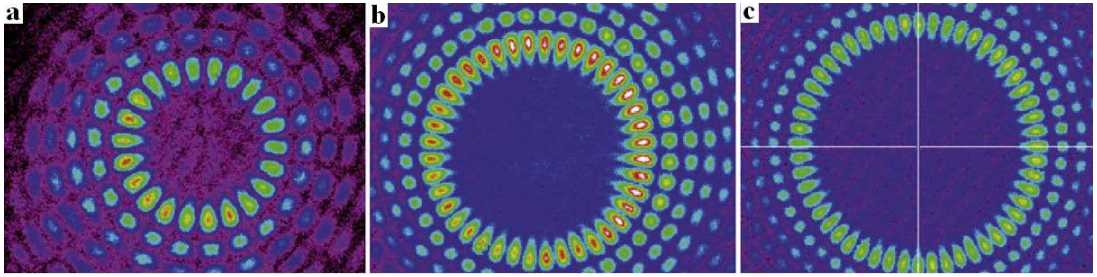


Schematic of a resonator showing „imaging”(*I*) and „focusing” (*F*) positions of a thin lens.

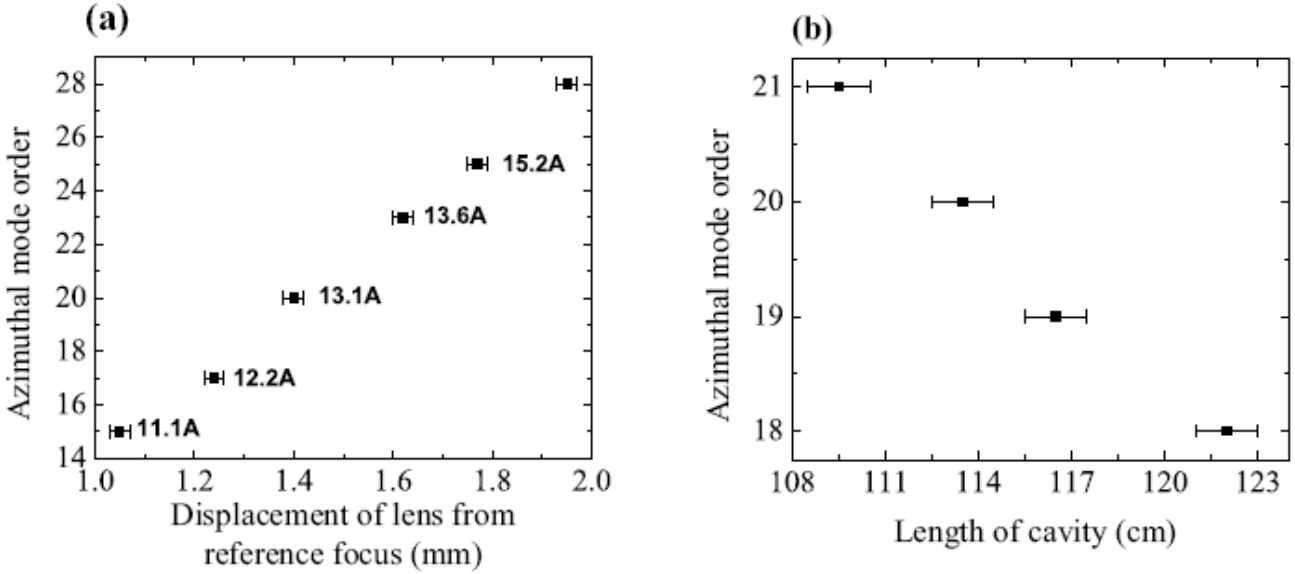


Ray tracing in a plane-parallel resonator containing a lens with spherical aberration.

Dependence of the azimuth index, *m* of hollow LG_{pm} modes on intra-cavity lens shifts and length of the cavity.

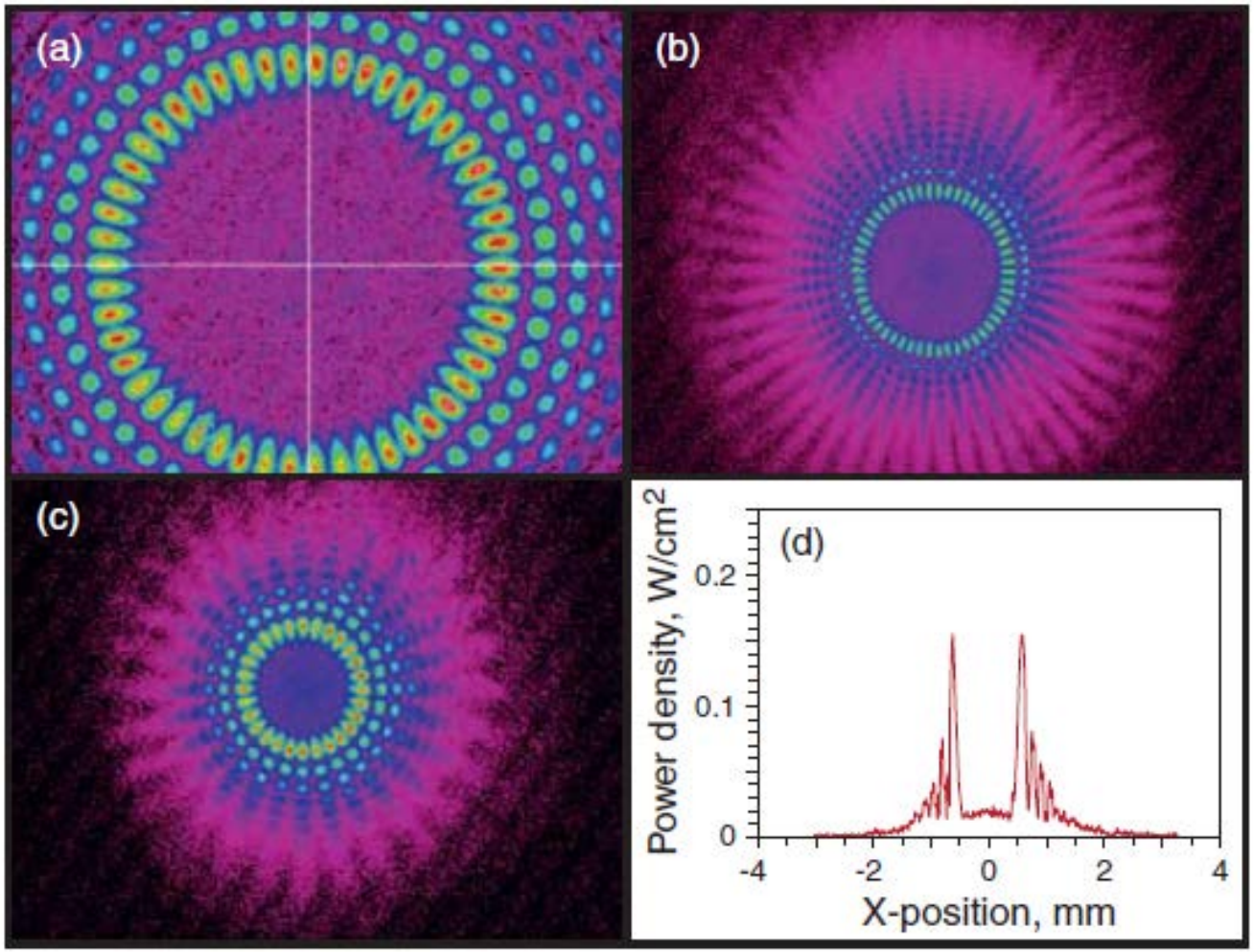


Near-field images of hollow higher order LG_{pm} modes with azimuth indices:(a) m=11;(b) m=20;(c) m=26 (1-10mW, θ=2-5mrad, λ≈1,03μm).



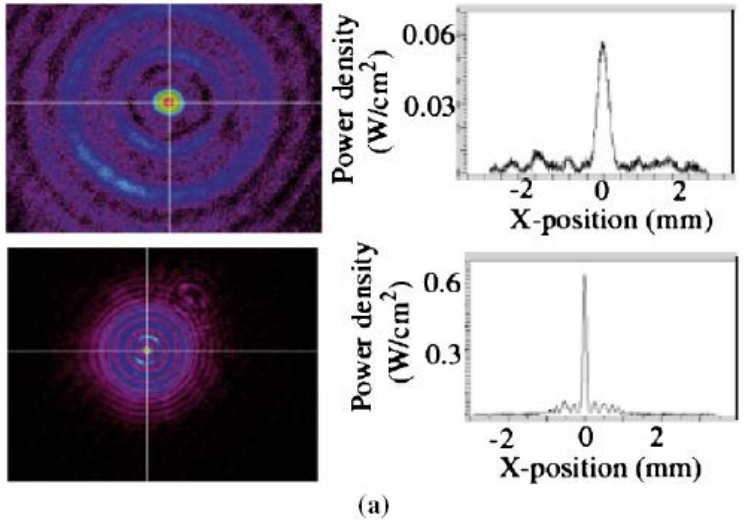
Azimuth index, m of hollow LG_{pm} modes on:(a) lens apex shift from the reference point, $d_{apex} \approx f_{ax}$ (threshold LD currents are indicated), L= 114 cm; (b) length of the cavity, L.

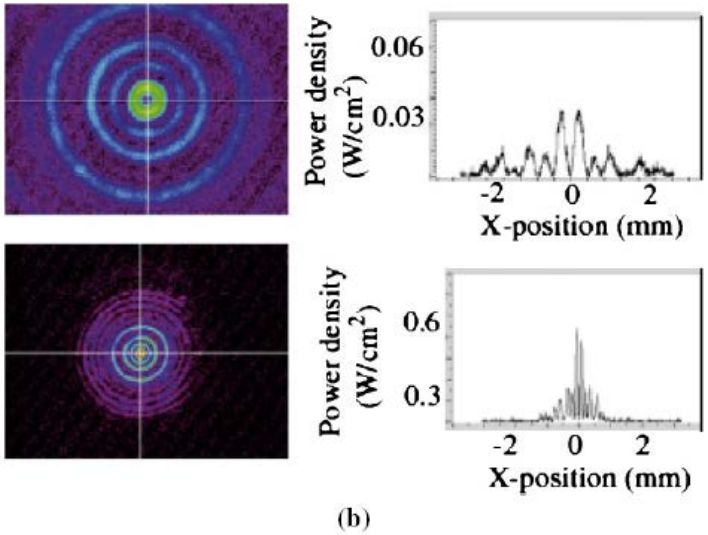
CCD camera images of near- and far-field patterns of $LG_{10,25}$ and $LG_{7,14}$ modes



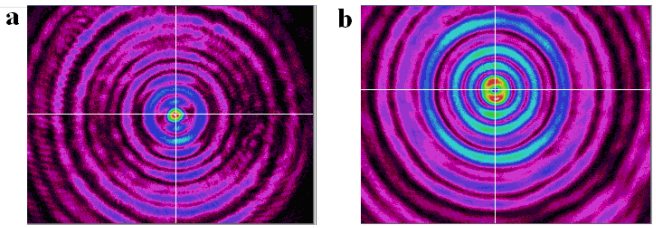
Images of near- (a) and far- (b) field patterns of $LG_{10,25}$ mode and far-field of $LG_{7,14}$ mode (c) with the corresponding intensity profile (d) (1-10mW, θ=2-4 mrad, λ≈1,03μm).

Bessel-like LG_{p0}, LG_{p1}^{*} modes with a highly directional propagation of the central maximum (minimum)

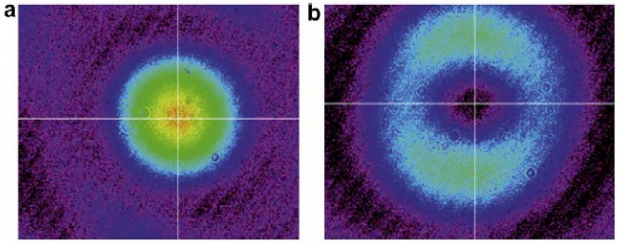




Near- and far-field images of Bessel-like LG_{pm} multi-ring beams with central maximum (a) and minimum (b) shown clearly in the corresponding intensity profiles near each image.

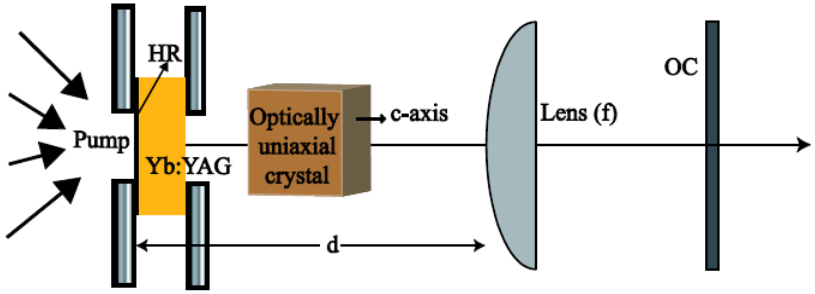


Images of Bessel-like LG_{pm} modes in near-field: (a) p = 11, m = 0; (b) p = 11, m = 1; 1-10 mW, λ≈1,03μm, θ=(2-5)x10^{-3} rad.

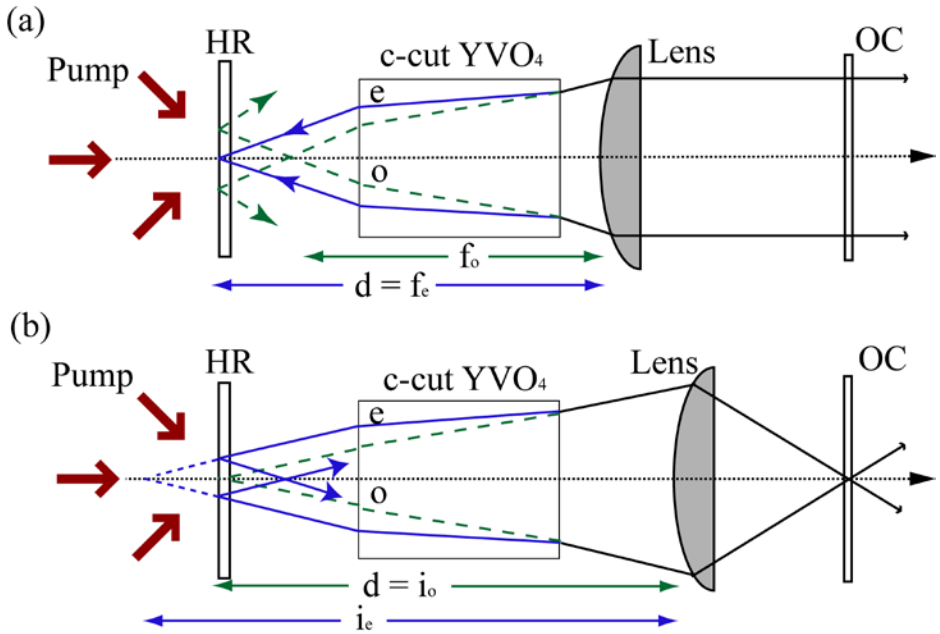


Images of the central core of Bessel-like LG_{pm} beams with central peak (a) and hole (b) at 11 m from the OC. The size of CCD camera frame is 6,4x4,8mm.; λ≈1,03μm, θ_{centr} = (0,9-3)x10^{-4} rad.

LG vector modes selection in the LD pumped cw Yb:YAG ceramic laser using an intra-cavity lens and a birefringent c-cut uniaxial crystal

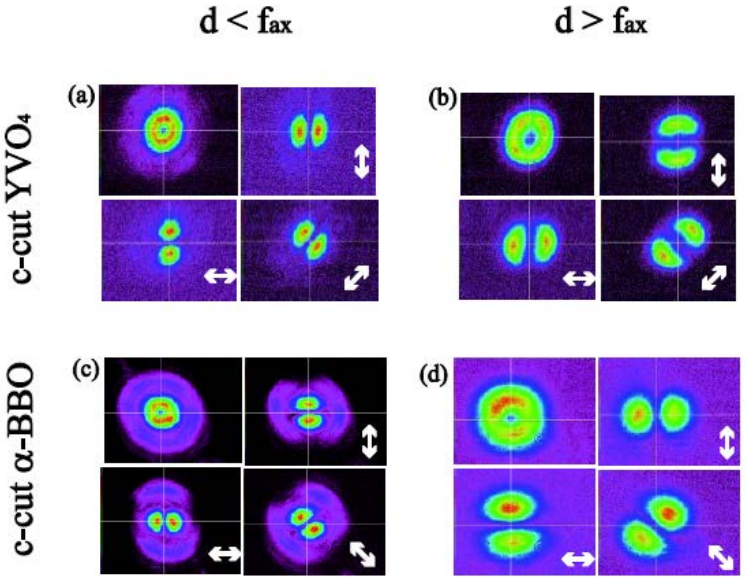


Scheme of the Yb:YAG ceramic laser with radially polarized (RP) or azimuthally polarized (AP) output (10-60mW, λ≈1,03μm, L=40-120cm, f=35-200mm).



Schemes of mode selection with an intra-cavity *c*-cut YVO4 crystal: (a) AP mode selection at "focusing" ($d = (f_e)_{ax}$) and (b) RP mode selection at "imaging" ($d = i_o$) lens positions.

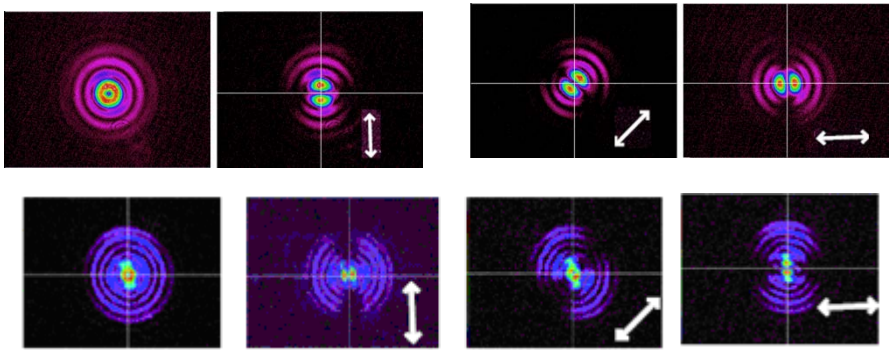
Radially polarized (RP) or azimuthally polarized (AP) doughnut-like modes (a-d) and multi-ring higher order modes (e, f) at the output of cw Yb:YAG ceramic laser



Images in near-field of AP and RP doughnuts generated by Yb:YAG laser with *c*-cut YVO4 (a, b) or α-BBO (c, d) crystals and the lens, f = 10cm placed at distances $d < f_{ax}$ or $d > f_{ax}$ from HR, L=114cm; λ≈1,03μm, 10-60mW.

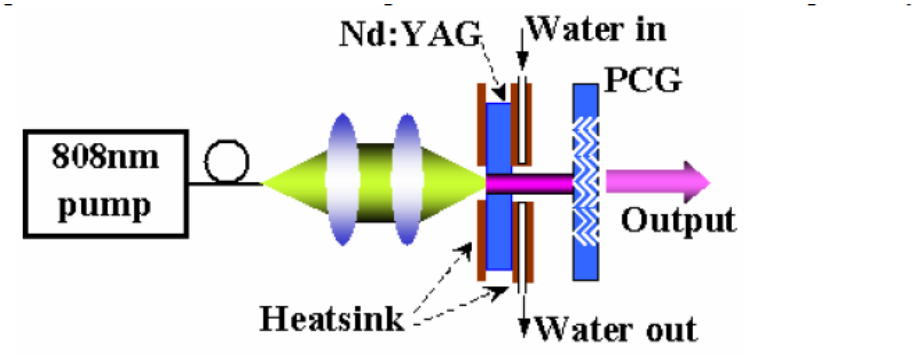
(e)

(f)

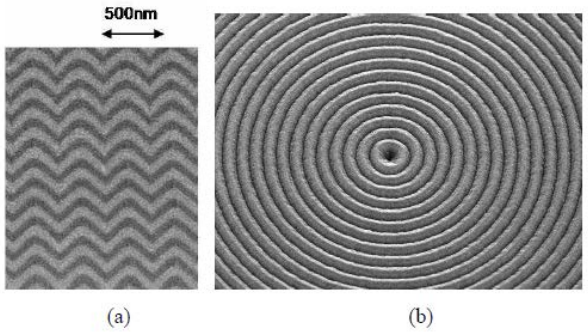


Images of modes in far field, L =114cm, f =3.5cm : (e) 3-ring RP mode with α-BBO; (f) 6-ring AP mode with YVO_4. The transmission axis of the external linear polarizer placed before the CCD camera is indicated by arrows wherever used.

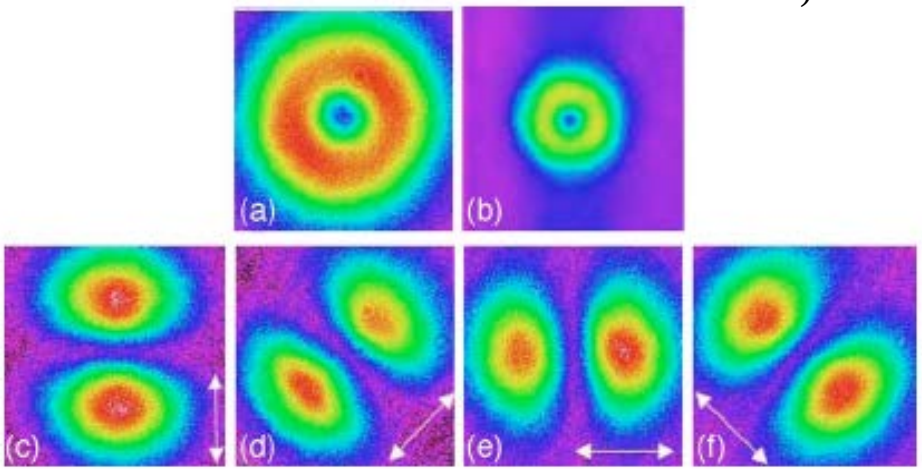
0,6 W radially polarized cw Nd:YAG ceramic laser with a polarization selective mirror



End-pumped and water-cooled Nd:YAG (0,45 at%, Ø15x1,9mm) ceramic laser with a PCG output coupler, λ=1,064μm, L=6,5cm. Pump:3-5W at λ≈0,8μm.



Images of the photonic crystal grating (PCG) mirror obtained by scanning electron microscopy: (a) cross section and (b) surface view (the pitch of concentric corrugations is 466 nm).



(a)-Far- and (b)- near-field intensity distributions of the RP output beam; (c)–(f) variations of far-field distributions after the beam passage through the linear polarizer (transmission axis indicated by arrows). Polarization extinction ratio - 60:1.

Conclusion

Main features of the Laguerre-Gaussian modes selection study:

- new methods of LG scalar and vector modes selection;
- LD pumped Nd:YAG and Yb:YAG ceramic lasers with tunable generation on scalar and vector LG modes from low to high orders;
- demonstration of scalar LG_{pm} modes (*p*-radial, *m*-azimuth indices) of record-high orders;
- observation of multi-ring Bessel-like LG_{p0} and LG_{p1}* modes with highly directional propagation of the central peak or minimum;
- ceramic lasers for cw and pulsed generation of radially (RP) and azimuthally (AP) polarized doughnut beams with high modal symmetry, polarization purity and efficiency;
- observation of RP and AP LG vector modes of high orders .

The large variety of LG scalar and vector beams from the developed ceramic laser schemes should find applications in different fields of science and technology.

List of publications by ILS/UEC (Tokyo) on Laguerre- Gaussian modes selection in Nd:YAG and Yb:YAG ceramic lasers

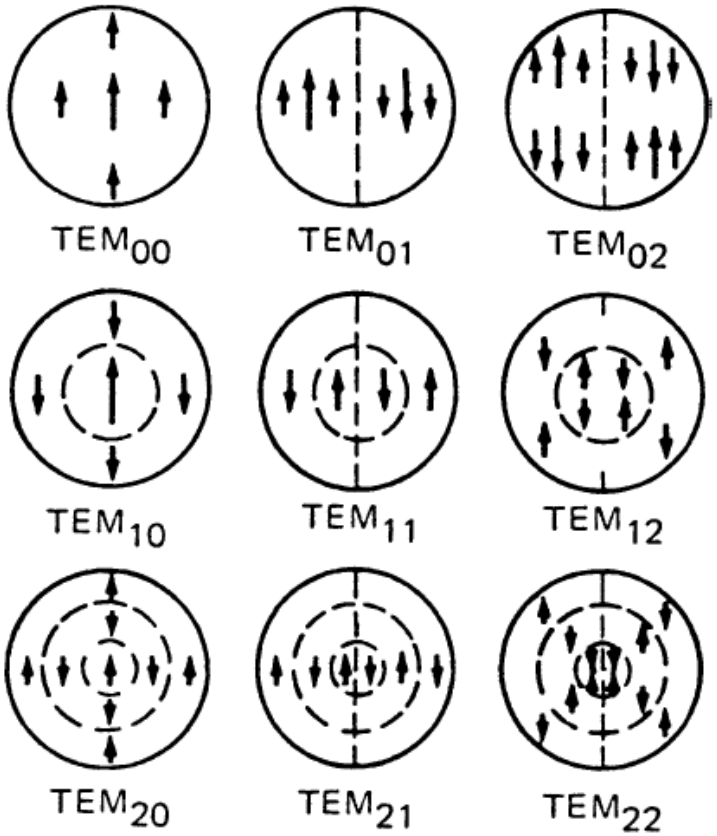
1. J.-F.Bisson, A. Shirakawa, Y.Sato, Yu. Senatsky, and K.Ueda: Opt. Rev.**11**(2004)353.
2. J.-F. Bisson, K.Ueda, Yu.Senatsky: Laser Phys. Lett. **2** (2005) 327.
3. J.-F. Bisson, J. Li, K. Ueda, Yu. Senatsky: Opt. Express **14** (2006) 3304.
4. J. Li, K.Ueda, L.Zhong, M. Musha, A.Shirakawa, T.Sato: Opt. Express **16** (2008)10841.
5. J. Li, K.Ueda, M.Musha, L.Zhong, and A.Shirakawa: Opt. Lett. **33**(2008)2686.
6. J. Li, A. Shirakawa, K. Ueda, D. Lin, and L. Zhong: Review of Laser Engineering **37** (2009)806.
7. J.Li, D. Lin, L.Zhong, K. Ueda, A. Shirakawa, M.Musha, and W.Chen: Laser Phys. Lett. **6**(2009)711.
8. Yu.Senatsky, J.-F. Bisson, A.Shelobolin, A. Shirakawa, and K. Ueda:Las.Phys.**19**(2009) 911.
9. M.Thirugnanasambandam, Yu. Senatsky, and K. Ueda: Las. Phys. Lett.**7** (2010)637.
10. M. Thirugnanasambandam, Yu. Senatsky, A.Shirakawa, and K. Ueda: Opt. Materials **33** (2011)675.
11. M.Thirugnanasambandam, Yu. Senatsky, K. Ueda: Opt. Express **19** (2011) 1905.
12. Yu. Senatsky, J.-F. Bisson, J. Li, A.Shirakawa, M. Thirugnanasambandam, and K. Ueda:Opt. Rev.**19** (2012)201.

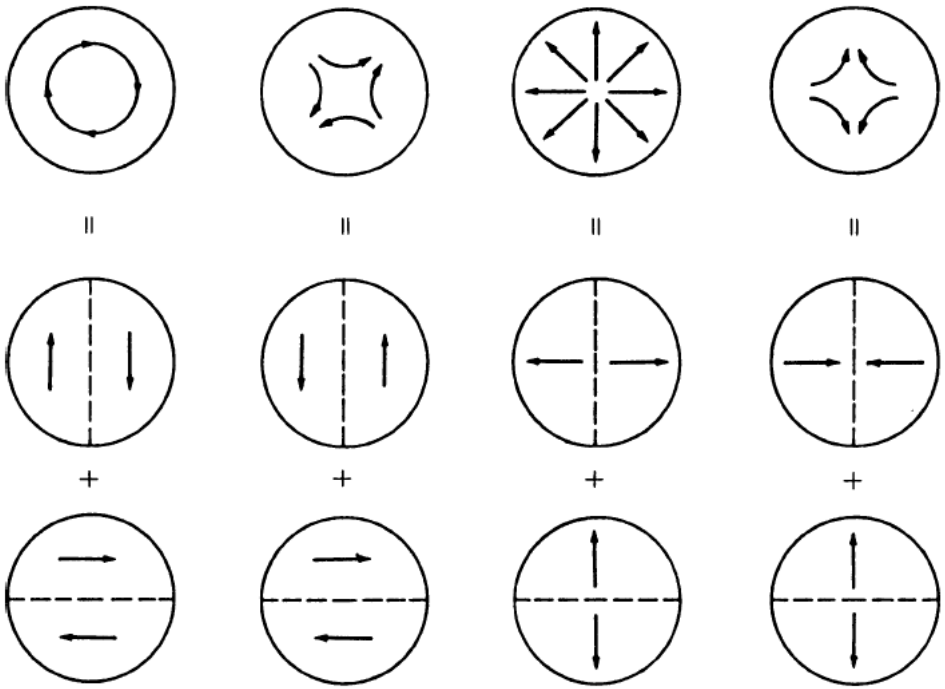
Experiments on Laguerre-Gaussian modes selection in DPSSLs

Laser media, pump scheme	mode selection technique	mode types	beam parameters	references
LG scalar modes selection				
Nd:YAG, e-p*	pump spot/mode waist ratio control	LG_{p0}, p=0-9	cw, λ_{las}=1.064 μm	106
Nd:YAG, e-p*	doughnut-shaped diffractive pumping	LG_{0m}, m=1-240	10 Hz, 0.1 mJ, 50-2000 ns pulses, λ_{las}=1.064 μm	80, 81
Nd:YAG, e-p	opaque disk at mirror	LG_{0m}, m=4-8	cw, λ_{las}=1.064 μm	121
Nd:YAG, s-p	spot-defect mirror	$LG_{0\pm m}$, m=1-8	cw, λ_{las}=1.064 μm	75
Nd:YVO_4, e-p	doughnut-shaped pumping	LG_{0m}, LG_{0m}^*, m=0-23	cw, λ_{las}=1.064 μm	40, 41
Nd:YVO_4, s-p	thermal lens	$LG_{0\pm1}$	cw,7.7W, λ_{las}=1.064 μm	100
Nd:YVO_4,s-p	thermal lens	$LG_{0\pm1}$	16.6 W; 50-400 kHz,10-40 ns pulses, λ_{las}=1.064 μm	102
Nd:YVO_4, e-p	doughnut shaped pumping	$LG_{0\pm1}$	cw, 12 mW, λ_{las}=1.064 μm	124
Nd:YVO4, e-p	pump spot/mode waist ratio control	LG_{p0}, p=0-8	8.5W, 20-80 kHz, 7-16ns pulses, λ_{las}=1.064 μm	114
Nd:$GdVO_4$, s-p	thermal lens	$LG_{0\pm1}$	cw,17.8W, λ_{las}=1.064 μm	101
Yb:YAG, e-p	intra-cavity lens with spherical aberration	LG_{pm}, LG_{pm}^*, p=0-12, m=0-28	cw, 1-30 mW, λ_{las}=1.03 μm	87-89
LG vector modes selection				
Nd:YAG, s-p	polarization selective mirror	TM_{01}	cw, 4W, λ_{las}=1.064 μm	64
Nd:YAG, s-p	conical Brewster prism	TM_{01}	cw , 90 mW, λ_{las}=1.064 μm	65
Nd:YAG, s-p	c-cut YVO_4	TM_{01}, TM_{02}	cw, 1 W, λ_{las}=1.064 μm	71
Nd:YAG, s-p	reflectivity modulated polarization selective mirror	TM_{0n}, n=2,3,4,5	cw, 780 mW, λ_{las}=1.064 μm	72-74
Nd:YAG, s-p	spot-defect mirror	TE_{01}, TM_{01}, higher-order LG and BG modes	cw, λ_{las}=1064 nm	75
Nd:YAG, s-p	thermal lens	TM_{01}, TE_{01}	cw, 32W, λ_{las}=1,064μ	126
Nd:YAG, e-p	polarization selective mirror	TM_{01},TE_{01}	cw, 630 mW, λ_{las}=1.064 μm	83
Nd:YAG, e-p	polarization selective mirror	TM_{01},TE_{01}	(TM_{01}) 450 mW, 86 ns, 6.7 kHz; (TE_{01}) 512 mW, 40 ns, 11 kHz; λ_{las}=1.064 μm	84-86
Nd:YVO_4, s-p	c-cut Nd:YVO_4	TM_{01}	cw, 75 mW, λ_{las}=1.064 μm	66
Nd:$GdVO_4$, e-p,	c-cut Nd:$GdVO_4$	TM_{01}	cw, 164 mW, λ_{las}=1.064μm	70
Yb:YAG, e-p	polarization selective mirror	TM_{01}	cw, 10-275 W, λ_{las}=1.03 μm	24, 68
Yb:YAG, e-p	c-cut α-BBO/YVO_4, intra-cavity lens with spherical aberration	TM_{0n}, TE_{0n}, n=1-10	cw, 1-30 mW, λ_{las}=1.03 μm	90
Er:YAG, e-p	doughnut shaped pumping, thermal lens	TM_{01}	cw, 13 W, λ_{las}=1.645 μm	125

*- pumping by external laser source

Synthesis of vector LG modes from the linearly polarized scalar LG modes





Linearly polarized resonator mode configurations for circular mirrors

Synthesis of different polarization configurations from the linearly polarized TEM_{01} mode

W. Koechner: *Solid-State Laser Engineering* (Springer, Berlin, 2006) 6th ed.