Tuneable Gaussian to flat-top resonator by amplitude beam shaping

Sandile Ngcobo,[1,2] Kamel Ait-Ameur,[3] Igor Litvin,[2] Abdelkrim Hasnaoui,[4] and Andrew Forbes[1,2,*]

[1]*Council for Scientific and Industrial Research, P.O. Box 395, Pretoria 0001, South Africa*
[2]*School of Physics, University of KwaZulu–Natal, Private Bag X54001, Durban 4000, South Africa*
[3]*Centre de recherche sur les Ions, les Matériaux et la Photonique, UMR 6252 CEA-CNRS-ENSICAEN et Université de Caen, CIMAP-ENSICAEN 6 Bd Maréchal Juin, F-14050 Caen, France*
[4]*Faculté de Physique, Université des Sciences et de la Technologie Houari Boumédiène, B.P. n° 32, El Alia, 16111 Algiers, Algeria*
**aforbes1@csir.co.za*

Abstract: We outline a simple laser cavity comprising an opaque ring and a circular aperture that is capable of producing spatially tuneable laser modes, from a Gaussian beam to a Flat-top beam. The tuneability is achieved by varying the diameter of the aperture and thus requires no realignment of the cavity. We demonstrate this principle using a digital laser with an intra-cavity spatial light modulator, and confirm the predicted properties of the resonator experimentally.

©2013 Optical Society of America

OCIS codes: (140.3300) Laser beam shaping; (140.3410) Laser resonators; (070.6120) Spatial light modulators; (070.3185) Invariant optical fields.

References and links

1. F. M. Dickey, S. C. Holswade, and D. L. Shealy, *Laser Beam Shaping Applications* (Taylor and Francis, 2006).
2. F. M. Dickey and S. C. Holswade, *Laser Beam Shaping, Theory and Techniques* (Marcel Dekker, 2000).
3. J. A. Hoffnagle and C. M. Jefferson, "Design and performance of a refractive optical system that converts a Gaussian to a flattop beam," Appl. Opt. **39**(30), 5488–5499 (2000).
4. A. Laskin and V. Laskin, "Imaging techniques with refractive beam shaping optics," Proc. SPIE **8490**, 84900J, 84900J-11 (2012), doi:10.1117/12.930284.
5. I. A. Litvin and A. Forbes, "Intra-cavity flat-top beam generation," Opt. Express **17**(18), 15891–15903 (2009).
6. P. A. Bélanger and C. Paré, "Optical resonators using graded-phase mirrors," Opt. Lett. **16**(14), 1057–1059 (1991).
7. P. A. Bélanger, R. L. Lachance, and C. Paré, "Super-Gaussian output from a CO_2 laser by using a graded-phase mirror resonator," Opt. Lett. **17**(10), 739–741 (1992).
8. J. R. Leger, D. Chen, and Z. Wang, "Diffractive optical element for mode shaping of a Nd:YAG laser," Opt. Lett. **19**(2), 108–110 (1994).
9. I. A. Litvin and A. Forbes, "Gaussian mode selection with intracavity diffractive optics," Opt. Lett. **34**(19), 2991–2993 (2009).
10. J. R. Leger, D. Chen, and K. Dai, "High modal discrimination in a Nd:YAG laser resonator with internal phase gratings," Opt. Lett. **19**(23), 1976–1978 (1994).
11. J. C. Dainty, A. V. Koryabin, and A. V. Kudryashov, "Low-order adaptive deformable mirror," Appl. Opt. **37**(21), 4663–4668 (1998).
12. T. Y. Cherezova, L. N. Kaptsov, and A. V. Kudryashov, "Cw industrial rod YAG:Nd3+ laser with an intracavity active bimorph mirror," Appl. Opt. **35**(15), 2554–2561 (1996).
13. T. Y. Cherezova, S. S. Chesnokov, L. N. Kaptsov, V. V. Samarkin, and A. V. Kudryashov, "Active laser resonator performance: formation of a specified intensity output," Appl. Opt. **40**(33), 6026–6033 (2001).
14. M. Gerber and T. Graf, "Generation of super-Gaussian modes in Nd:YAG lasers with a graded-phase mirror," IEEE J. Quantum Electron. **40**(6), 741–746 (2004).
15. A. J. Caley, M. J. Thomson, J. Liu, A. J. Waddie, and M. R. Taghizadeh, "Diffractive optical elements for high gain lasers with arbitrary output beam profiles," Opt. Express **15**(17), 10699–10704 (2007).
16. S. Ngcobo, I. A. Litvin, L. Burger, and A. Forbes, "A digital laser for on-demand laser modes," Nat. Commun. **4**, 2289 (2013), doi:10.1038/ncomms3289.
17. A. Hasnaoui and K. Ait-Ameur, "Properties of a laser cavity containing an absorbing ring," Appl. Opt. **49**(21), 4034–4043 (2010).
18. A. Hasnaoui, T. Godin, E. Cagniot, M. Fromager, A. Forbes, and K. Ait-Ameur, "Selection of a LGp0-shaped fundamental mode in a laser cavity: phase versus amplitude masks," Opt. Commun. **285**(24), 5268–5275 (2012).
19. V. Arrizón, "Optimum on-axis computer-generated hologram encoded into low-resolution phase-modulation devices," Opt. Lett. **28**(24), 2521–2523 (2003).

20. V. Arrizón, U. Ruiz, R. Carrada, and L. A. González, "Pixelated phase computer holograms for the accurate encoding of scalar complex fields," J. Opt. Soc. Am. A **24**(11), 3500–3507 (2007).

1. Introduction

A laser beam with an intensity profile that is flat-top (or top-hat) is desirable in many applications [1]. Many techniques exist for the creation of flat-top beams external to the laser cavity [2–4], which can be accomplished with low loss albeit with some complexity in the optical delivery system (e.g., requiring careful alignment and fixed input beam parameters to the shaping elements). There are advantages to having such a beam profile as a direct output from a laser cavity (e.g., optimised energy extraction), however the methods of obtaining such beam shapes as the laser eigenmodes are quite complicated, and often involve custom made (expensive) diffractive optics, aspheric elements, graded phase mirrors or deformable mirrors [5–15]. Furthermore, all the solutions to date have been designed for a single mode and are not tuneable in the mode selection.

In this work we propose an alternative technique for obtaining a Flat–Top (FT) beam as the fundamental output of a laser cavity. Our technique requires only an intra-cavity opaque ring as an amplitude filter in combination with a standard circular aperture, in a conventional laser cavity. We show that by judicious choice of parameters such a cavity can be made to perform as a FT beam cavity, or a Gaussian beam cavity, by merely adjusting the circular aperture: the cavity is mode tuneable in an easy-to-implement manner, requiring neither new optics nor realignment of the elements. Furthermore the FT beam is found in the far field, thus significantly simplifying the delivery optics since no relay imaging is required. This differs from previous FT resonators where the FT beam is created only in the near field. A final departure point is that we verify our concept and theoretical predictions using a "digital laser" [16] comprising an intra-cavity spatial light modulator as a rewritable holographic mirror.

2. Concept and simulation

Our concept is based on the mode selective properties of a cavity comprising both an aperture and a ring obstruction, as illustrated in Fig. 1. We will show that the desired beams can be obtained by careful selection of the normalized radius $Y_a = \rho_a/w_0$ of the opaque ring of width h, and the normalised radius $Y_c = \rho_c/w_c$ of the circular aperture; here w_0 and w_c are the beam radii of the Gaussian beam in the bare cavity (without the ring of radius ρ_a and aperture of radius ρ_c) at the flat and curved mirror, respectively. Single pass studies [17,18] on the transmission of radial Laguerre-Gaussian beams through each component (separately) have indicated that when the aperture is "open" ($Y_c > 2$) all the radial modes have similar losses, while as it is closed so the Gaussian mode dominates with the lowest loss; in the latter scenario there is no radial mode selectivity by this element.
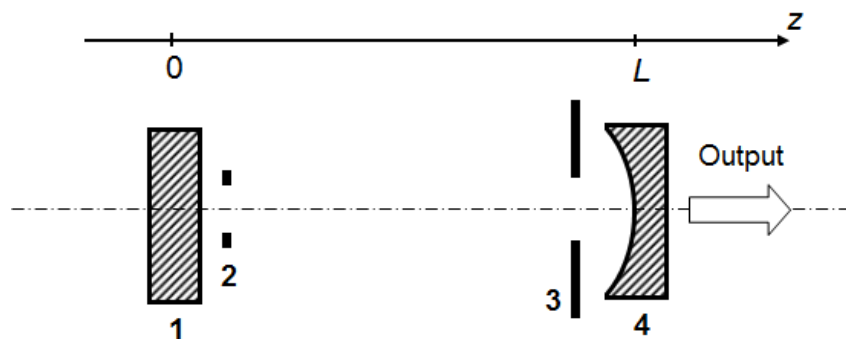

Fig. 1. A schematic representation of the concept. An absorbing ring (2) is placed at the plano (1) end of a plano-concave cavity. A standard circular aperture (3) is placed at the opposite end, and the mode is transmitted through the output coupler (4).

This is depicted through simulation in Fig. 2(a). The opaque ring on the other hand can be highly mode selective, and does not exhibit the monotonic behaviour of the aperture. Rather, there are normalised radii where the losses are inverted for the radial modes (lower radial modes have higher losses), and other radii where the losses for several radial modes would be the same or similar, as seen through simulation in Fig. 2(b).
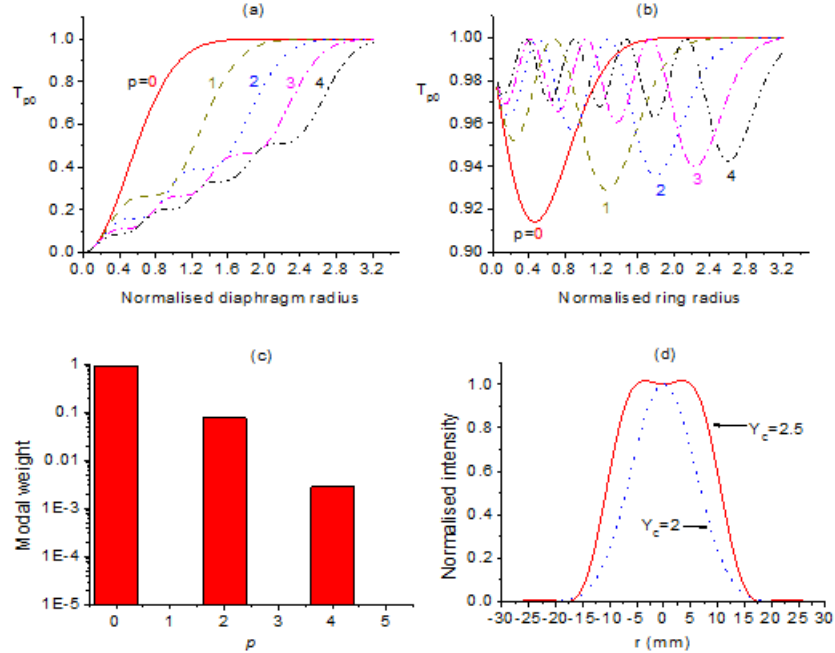

Fig. 2. (a) Single pass losses for radial Laguerre-Gaussian modes through an aperture, (b) Single pass losses for radial Laguerre-Gaussian modes through an opaque ring, (c) Predicted modal spectrum of radial (p) modes for $Y_a = 1.55$ and $Y_c = 2.5$, and (d) Predicted output modes from the cavity in the far field showing a quasi-Gaussian ($Y_c = 2$) and flat top beam ($Y_c = 2.5$). The simulations were performed with a normalised ring radius of $Y_a = 1.55$ and a ring width of $h = 20$ μm. The parameters of the cavity were selected to match the experiment, namely, $R = 500$ mm and $L = 252$ mm for $g \sim 0.5$ at a wavelength of $\lambda = 1064$ nm.

This suggests a simple approach to tuneability: if the normalized ring radius is chosen to allow particular Laguerre-Gaussian radial modes to lase simultaneously, then they will do so incoherently. If the aperture is open, so that the ring is the mode determining element, then our Fox-Li analysis predicts a flat-top beam as the output. As the aperture is steadily closed, so it becomes the mode determining element and the Gaussian mode is selected, based on substantially lower round trip losses. Hence only the aperture opening needs to change to control the mode.

Our simulation results, shown in Fig. 2, suggest that for $Y_a \approx 1.5$ the cavity eigenmode is a FT beam, the purity of which can be adjusted by varying Y_c. We find optimal settings of $Y_c = 2.5$ for a high quality FT beam, which can be approximated in shape by a super-Gaussian beam of order ~5. The incoherent modal spectrum, comprising three radial Laguerre-Gaussian modes, is shown in Fig. 2(c). Furthermore we predict that the FT beam can be transformed into a quasi-Gaussian beam by simply adjusting the circular aperture to $Y_c = 2.0$, while keeping Y_a. Since the FT beam is a incoherent sum of radial modes the shape remains invariant during propagation. The results are shown in the far field in Fig. 2(d) for both beams. If the circular aperture is opened further more exotic modes are found, for example, a donut mode at $Y_c = 2.6$.

3. Experimental setup and results

In order to test the simulated results we used the laser set–up shown in Fig. 3(a). The cavity was arranged in a Z-shape to allow the high power pump (808 nm) to pass through the gain medium (Nd:YAG) without interference from the aperture and ring mask. The stable plano-concave cavity had an effective length of 252 mm, with the circular aperture placed directly in front of the curved (R = 500 mm) output coupler of reflectivity 80%. The output mode could be measured in both the near field and far field with imaging or Fourier transforming optics. Care was taken to separate the lasing wavelength (1064 nm) from the pump light (808 nm) with suitable filters.
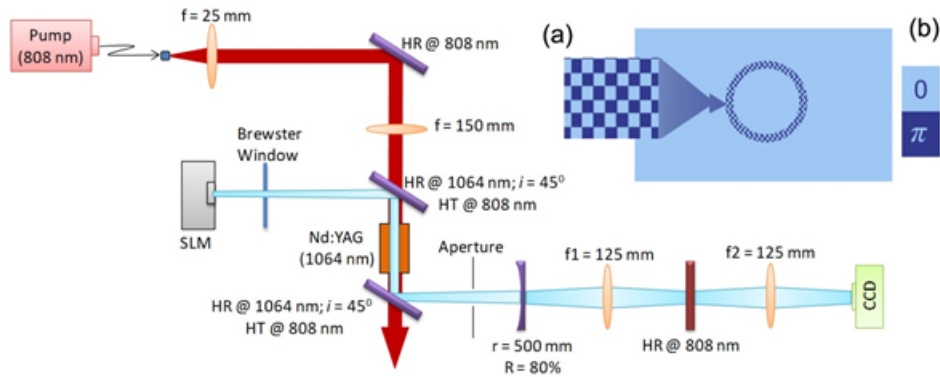

Fig. 3. (a) Schematic setup of an intra-cavity SLM with diagnostic and control equipment. The High Reflectors (HR) were used to reflect the 808 nm or 1064 nm wavelengths. (b) SLM phase screen acted as a flat-end mirror containing an opaque ring of 100 μm width.

An additional novel aspect of this experiment was the use of a "digital laser" [16]. One of the cavity mirrors in the digital laser setup is a rewritable phase-only spatial light modulator (SLM), forming a holographic end-mirror. The SLM was programmed with a digital hologram representing both the flat mirror and the opaque ring, as shown in Fig. 3(b). The digital laser allowed for easy optimisation of the ring radius as well as the ring thickness. To vary these parameters with lithographically produced rings of varying thickness and radius would be time consuming, and would require a realignment of the cavity for each setting. In the digital laser, a new ring could be created by merely changing an image on the control PC representing the desired digital hologram, without any realignment. The amplitude modulation employed to realise the ring was achieved by complex amplitude modulation [19,20] using high spatial frequency gratings in the form of so-called "checker boxes". On the other side of the cavity we had a variable circular aperture which was controlled manually in order to find the optimal value of Y_c. This standard aperture provided the tuneability of the mode.

The output from the digital laser is shown in Fig. 4, where the near field and the far field intensity profiles of the quasi-Gaussian (a) and Flat-top (b) beams are shown. In the first four panels (a-b) we have the results for a 20 μm width ring, while in the last four panels (c-d) we have the results for a 100 μm width ring. We note that the spatial intensity distributions are in good agreement with the simulated Fox-Li results in Fig. 2(d). Moreover, as predicted by theory, the desired shapes are found in the far field too. The field patterns are also found at values of Y_a and Y_c close to those predicted by theory, differing by less than 10%. The small deviation can be attributed to minor mode size errors, e.g., due to small thermal lensing or refractive index errors.
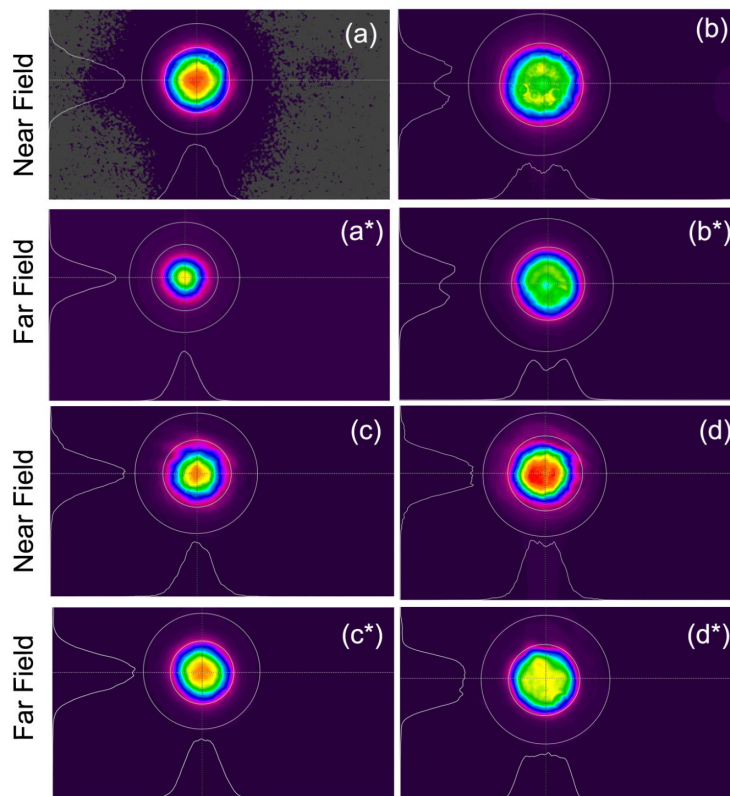
Fig. 4. Experimentally obtained near field and far field images of the Gaussian beam and Flat-top beam for ring width settings of (a-b): 20 μm and (c-d): 100 μm. Gaussian beam (a and a*) and Flat-top beam (b and b*) for $Y_a = 1.4$, a ring width of 20 μm, and $Y_c = 2.0$ (Gaussian) and 2.3 (FT). Gaussian beam (c and c*) and Flat-top beam (d and d*) for $Y_a = 1.4$, a ring width of 100 μm, and $Y_c = 2.0$ (Gaussian), 2.3 (FT). These values are in good agreement with theory.

Slope efficiency measurements, Fig. 5, reveal that the FT beam has the highest slop efficiency but also the highest threshold as compared to the quasi-Gaussian beam selected by the ring cavity. The FT beam slope efficiency is approximately 2 × that of the quasi-Gaussian. This can be explained by the fact that the FT beam has a much larger gain volume than the quasi-Gaussian mode and is better matched to the pump beam in size and shape. For comparison the data for a Gaussian beam without any ring is also shown; this was achieved with no opaque ring programmed on the SLM and a normalized circular aperture set to $Y_a = 2.0$ on the curve mirror (i.e., the standard approach to Gaussian mode selection). The quasi-Gaussian and Gaussian mode show little difference when the ring width is small (20 μm), indicating that indeed the perturbation from the ring is minimal in the case of selecting the quasi-Gaussian, and thus it may indeed be considered as a Gaussian mode, in agreement with the theoretical prediction. It has been suggested previously [18] that in some cases amplitude masks do not lead to higher losses, and this could be the situation here too. When the ring width increases the quasi-Gaussian departs further from the ideal Gaussian mode and the lasing threshold increases.
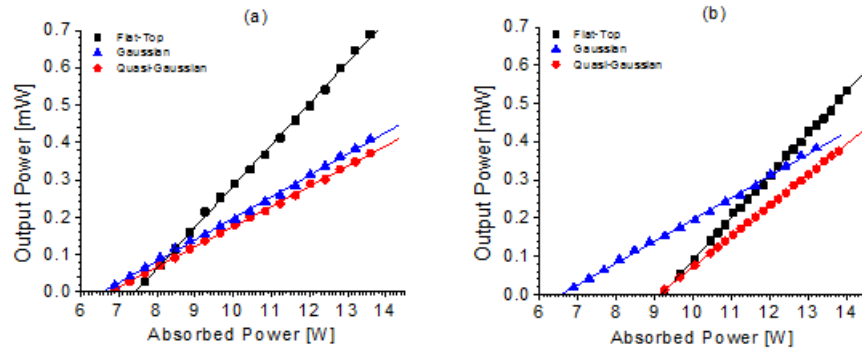
Fig. 5. The slope efficiencies of the FT beam, quasi Gaussian beam and Gaussian beam for (a) 20 μm and (b) 100 μm ring width.

Finally we point out that while we have used the digital laser to prove the principle, one would not use the intra-cavity SLM approach in a high power system. Rather, one would make use of custom optical elements to implement the ring aperture, thereby increasing the damage threshold and lowering the losses, to produce a more efficient and practical system.

4. Conclusion

In conclusion, we have conceived of and then demonstrated a novel laser cavity that is mode tuneable. We have shown that by simply adjusting the diameter of a standard circular aperture in the cavity, the mode can be selected from the ubiquitous Gaussian to a Flat-top beam. The ring mask was implemented with an intra-cavity holographic mirror for the convenience that this allows in testing the design parameters, but a high power version, optimised for power extract, would necessarily be made with standard optics and lithographic processing techniques to eliminate the SLM losses.