Journal of Luminescence 170 (2016) 750–754

Contents lists available at ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

Emission of a propagation invariant flat-top beam from a microchip laser

Darryl Naidoo [a], A. Harfouche [b], Michael Fromager [c], Kamel Ait-Ameur [c], Andrew Forbes [d,*]

[a] Council for Scientific and Industrial Research, National Laser Centre, P.O. Box 395, Pretoria 0001, South Africa
[b] Faculté de Physique, Université des Sciences et de la Technologie Houari Boumédiène, B.P. no 32, El Alia, 16111 Algiers, Algeria
[c] Centre de Recherche sur les Ions, les Matériaux et la Photonique, Unité Mixte de Recherche de Recherche 6252, Commissariat à l'Energie Atomique, Centre National de la Recherche Scientifique, Université de Caen Basse Normandie, Ecole Nationale Supérieure des Ingénieurs de Caen, Boulevard Maréchal Juin, F14050 Caen, France
[d] School of Physics, University of the Witwatersrand, Private Bag 3, Johannesburg 2050, South Africa

ARTICLE INFO

Article history:
Received 21 May 2015
Accepted 28 September 2015
Available online 21 October 2015

Keywords:
Microchip
Optical feedback
Flat-top beam
Gaussian beam

ABSTRACT

Light beams with a flat-top intensity profile have found many applications in both pure and applied studies, but are not the natural modes of conventional light sources such as lasers. Moreover, such light beams are also not the eigenmodes of the wave equation in a vacuum and so change their intensity profile dramatically during propagation. Here we overcome both these limitations and create a propagation invariant flat-top beam from a microchip laser. By optical feedback into the excited medium we are able to create emission that is an incoherent mix of two spatial modes, a Gaussian and a donut, so that the sum is a flat-top beam that maintains its shape to infinity. Such miniature sources that emit structured light will be attractive for integrated light-based technologies.

1. Introduction

A laser beam profile that is characterized by an intensity with a central flat plateau with steep skirts at the edges, often referred to as a flat-top beam, is extremely sought after in many diverse fields [1]. These beams have found applications in corneal treatment [2], efficient proton acceleration [3] and laser micromachining [4]. Many techniques have been exploited in the selection of flat-top beams and are traditionally separated into two classes. The first class typically involves the reshaping of some Gaussian beam *external* to a laser cavity and may be accomplished with high efficiency by either diffractive [5,6], refractive [7,8] and even interference phenomena [9]. Although these approaches may be lossless they are generally limited to having fixed input parameters (eg., beam size and profile). The second class explores *intra-cavity* means and the advantages of this class are highly attractive due to a potentially higher energy extraction. The realization of flat-top beams through intra-cavity techniques has been explored through amplitude and phase control, but always requires complex custom optics in the form of deformable mirrors, aspheric optics, graded phase mirrors, diffractive optics and recently spatial light modulators [10–22], rendering these processes particularly expensive. Unfortunately flat-top beams are not eigenmodes of the free space wave equation and so change shape dramatically during propagation. Consequently flat-top beams are usually created at specific planes, e.g., for materials processing, and relay imaged if required at distances far from the creation plane. It also means that even within the laser cavity the flat-top beam exists only at a single plane, usually at the output coupler. Although microchip lasers have been in existence for many years now they have not been traditionally used to produce structured light fields as intra-cavity beam shaping elements are not permissible in such lasers due to the compact design [23–25].

In this paper we demonstrate the generation of a propagation invariant flat-top beam from a monolithic microchip laser (MML). We simultaneously excite a Gaussian beam (LG_{00}) and a donut beam (LG_{01}) using an optical feedback technique. As these modes extract from disparate regions of the gain and differ in frequency, they lase incoherently. Moreover, the ratio of their divergences is constant during propagation. The consequence is a superposition that has a flat-top intensity profile that does not change with propagation. We discuss the theoretical considerations in Section 2 followed by the experimental realization and results in Sections 3 and 4, respectively.

* Corresponding author at: Council for Scientific and Industrial Research, National Laser Centre, P.O. Box 395, Pretoria 0001, South Africa.
E-mail address: andrew.forbes@wits.ac.za (A. Forbes).

http://dx.doi.org/10.1016/j.jlumin.2015.09.035
0022-2313/

2. Concept and theory

2.1. Optical modes

Flat-top beams can be described by a super-Gaussian function where the parameter N describes the steepness of the edges and flatness of the central region, and w is the characteristic scale of the field [26]:

$$I(r)=\exp\left(\frac{-2r^{2N}}{w^{2N}}\right) \tag{1}$$

It is possible to approximate this function by adding two functions

$$I(r)=|LG_{00}|^2+|LG_{01}|^2 \tag{2}$$

where the Laguerre–Gaussian modes (LG_{pl}) are of radial and azimuthal orders p and l, respectively:

$$LG_{pl}=\sqrt{\frac{2p!}{\pi(p+|l|)!}}\frac{1}{w(z)}\left(\frac{\sqrt{2}r}{w(z)}\right)^{|l|}L_p^{|l|}\left(\frac{2r^2}{w(z)^2}\right)\times\exp\left(\frac{-r^2}{w(z)^2}-\frac{ikr^2}{2R(z)}\right)\exp\left(-i(2p+|l|+1)\arctan\left(\frac{z}{z_R}\right)\right)\exp(-il\varphi) \tag{3}$$

where r and φ are the radial and azimuthal coordinates respectively, $L_p^{|l|}$ is the generalized Laguerre polynomial and all other terms have their usual meaning (z_R: Rayleigh range, $R(z)$: radius of curvature, $w(z)$: Gaussian beam width). The two modes as well as their sum are shown in Fig. 1. In the selection of a shape invariant flat-top beam the requirement is that one mode should be a Gaussian beam (LG_{00}) and the other a donut-shaped beam (LG_{01}). The first mode will fill the hollow center of the second mode such that the resulting beam approximates a flat-top intensity profile, as is illustrated in Fig. 1. However, as indicated by Eq. (2), the modes must be added in their intensities and not their fields. Previously this has been achieved external to laser cavities by adding the modes in Eq. (2) with orthogonal polarizations [27,28]. Now we demonstrate that it can be done internal to a microchip laser, where the incoherence is due not to orthogonal polarizations but to the low gain overlap of the respective modes and differing lasing frequencies. The spatial emission from the gain comprises two incoherent modes.

Note that this flat-top profile remains invariant in its transverse shape along the propagation axis, apart from a lateral expansion. This can be understood since the divergence of the two modes has a constant ratio and therefore their sizes have the same ratio in all space (both expanding). Consequently, the flat-top beam maintains its intensity profile but expands as it propagates.

2.2. Optical feedback

The simultaneous excitation of an LG_{00} mode and LG_{01} mode in a monolithic laser microchip is restricted as intra-cavity beam shaping elements are not permissible. One can also anticipate that the competition between these two modes would be relatively low since they effectively extract their energy from distinct regions of the laser gain medium. In order to force the MML to emit simultaneously on several transverse modes we form a three-mirror laser cavity as illustrated in Fig. 2. Such coupled cavities have been explored theoretically before [29,30] but not applied to

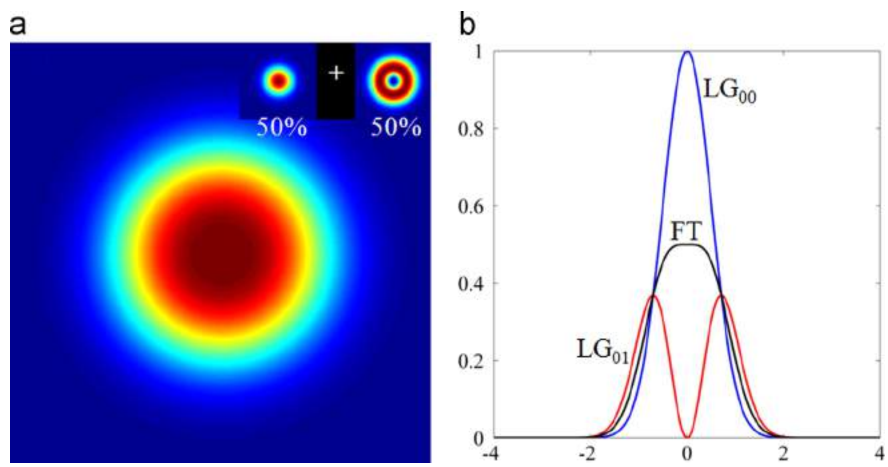

Fig. 1. The selection of a shape invariant flat-top beam (FT) through the incoherent superposition of an equally weighted LG_{00} and LG_{01} beam. The transverse profile of the FT is characterized by a (a) flat plateau with steep skirts as further illustrated in its (b) cross-section. The LG_{00} mode will fill the hollow center of the donut-shaped mode, LG_{01}, (b) as illustrated in their cross-sectional intensity profiles, such that the resulting beam approximates a flat-top intensity profile.

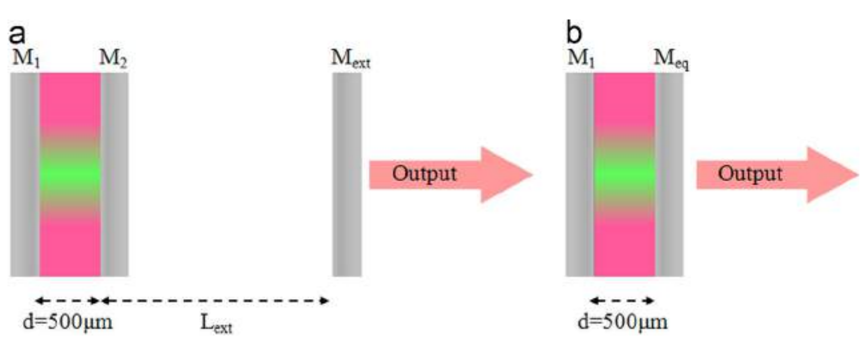

Fig. 2. Schematic of the three-mirror laser made up of a main resonator (MML) and an external passive resonator. Conceptually this arrangement is mimicked by replacing the external cavity (mirror M_2 to mirror M_{ext}) with an equivalent mirror M_{eq}.

microchip lasers. In Fig. 2 we note two main Fabry–Perot cavities: that between mirrors M_1 and M_2, and that between mirrors M_2 and M_{ext}.

It has been shown theoretically that one can reduce the three mirror cavity back to the original MML cavity by suitable adjustment to the reflectivity of mirror M_2 to form an "equivalent" mirror, M_{eq}. It is beyond the scope of this paper to provide a full theoretical analysis, but the reader is referred to Ref. [29] for further details. When we refer to the output coupler reflectivity we refer either to M_{ext} in Fig. 2(a) or M_{eq} in Fig. 2(b). The optical feedback system leads to a mode specific reflectivity for the output coupler, R_{pl}. This is because the resonance condition of the Fabry–Perot cavity is influenced by the Gouy phase shift of the beams, given by the 3rd exponential term in Eq. (3). This phase shift is mode dependent through the indices p and l, and so the output reflectivity is also mode specific. It can be shown that the reflectivity of the output mirror M_{eq}, and hence the mode gain/loss, is sensitive to.

(1) the transverse mode order;
(2) the ratio Z_R/L_{ext}, where Z_R is the Rayleigh range of the incident beam;
(3) the microscopic phase shift $\Delta\Phi$ which results from a modulo operation applied to the macroscopic phase shift $2kL_{ext}$:

$$\Delta\Phi = \mathrm{mod}(2kL_{ext}, 2\pi) = 2kL_{ext} - \mathrm{INT}(2kL_{ext}/(2\pi)) \times 2\pi$$

For the sake of clarity, we will stress on the variations of the reflectivity, R_{pl} for the LG_{00} and LG_{01} beams only and for $\Delta\Phi=180°$ and $\Delta\Phi=220°$; the variations are illustrated in Fig. 3 (a) and (b), respectively. It can be seen that for $\Delta\Phi=180°$ the laser will emit the LG_{00} mode independent of the external distance L_{ext} as it is reflected more efficiently. In contrast, for $\Delta\Phi=220°$, the distance L_{ext} is critical:

(1) for $L_{ext} < Z_R/2.5$ the laser will emit a donut mode although the pumping is Gaussian in shape;
(2) for $L_{ext} \approx Z_R/2.5$ the laser will emit simultaneously on the LG_{00} and LG_{01} modes since; $R_{00}=R_{01}$and the laser output can be a flat-top profile in both the near and far-field.
(3) for $L_{ext} > Z_R/2.5$ the laser beam is a Gaussian beam.

Thus by adjusting the distance L_{ext} it is possible to adjust the losses for each mode in the cavity. This is the central idea behind selecting the desired mode.

3. Experimental set-up and results

Our microchip, polished flat and parallel on opposing sides, consisted of a Nd:YVO_4 gain medium of dimensions $5\times5\times0.5\ \mathrm{mm}^3$ with dielectric mirrors deposited directly onto the polished surfaces that perform as the laser cavity mirrors with reflectivities of $R_1=99.5\%$ for the back mirror and $R_2=98\%$ for the out coupling mirror operating at 1064 nm as presented in Fig. 4. The MML was optically pumped by a single mode fiber-coupled diode laser emitting a Gaussian beam at 808 nm with a maximum power of 160 mW. The incident Gaussian pump beam was collimated to a second moment diameter of $4\sigma_x=1.912$ mm and $4\sigma_y=1.911$ mm, and focused into the microchip with a lens of focal length, $f=100$ mm, which resulted in a Gaussian beam of $4\sigma_x=71.9$ μm and $4\sigma_y=71.4$ μm. The size of the pump beam could be controlled through the choice of the focal length of the lens, without changing the intensity profile of the shaped light. The optical feedback into the microchip in the selection of a shape invariant flat-top beam was provided by a laser line filter (M_{ext}) optimized for reflection at 808 nm and transmission at 1064 nm. The distance at which the line filter was positioned from M_2 was variable through a translation stage.

With no line filter the output from the cavity was a Gaussian mode, as shown in Fig. 5(a) with its far field profile shown in the inset. When the line filter was inserted at a distance of $L_{ext}=25$ mm ($L_{ext} < Z_R/2.5$) we find that in the near field we obtain a shape invariant vortex beam, as shown in Fig. 5(b) with its corresponding far field profile illustrated in the inset. When $L_{ext} \approx Z_R/2.5$ we find a good approximation to a flat-top beam, as shown in Fig. 5(c) and verified by its far field profile shown in the inset.

In an attempt to vary L_{ext} and progress beyond the operating condition of $L_{ext} < Z_R/2.5$ ($L_{ext}=25$ mm) as illustrated in Fig. 6(a), the line filter was positioned at a distance of 40 mm from the

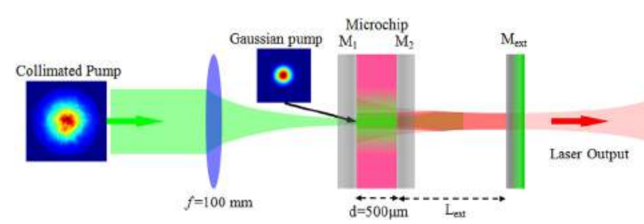

Fig. 4. Schematic of the experimental setup for optically pumping a microchip laser with a Gaussian pump. The optical feedback mirror was a laser line filter (M_{ext}) placed after the MML.

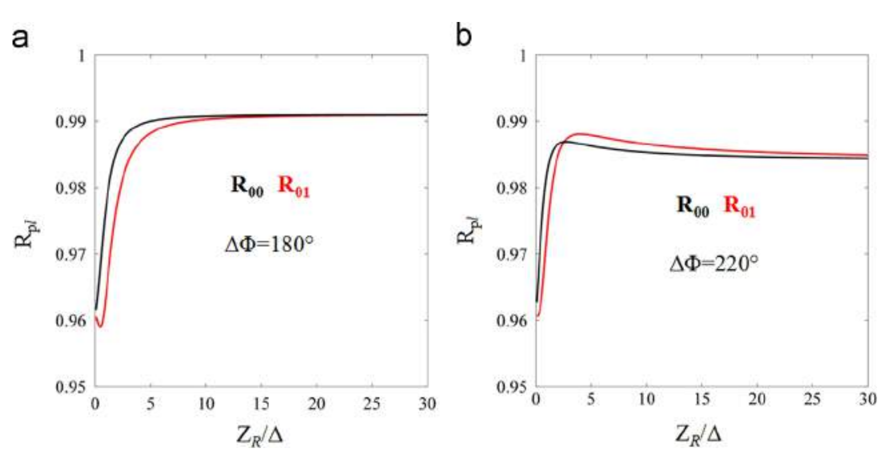

Fig. 3. The variations of the Michelson reflectivity, R_{pl} for the LG_{00} and LG_{01} beams for (a) $\Delta\Phi=180°$ and (b) $\Delta\Phi=220°$.

microchip and the respective near and far field profiles are illustrated in Fig. 6(b). We optimize L_{ext} such that we are in the $L_{ext} \approx Z_R/2.5$ regime and find that at a distance of 60 mm from the microchip the near field profile as illustrated in Fig. 6(c) is a well defined flat-top beam that retains its transverse profile in the far field (inset of Fig. 6(c)) which is in excellent agreement with the theoretical prediction presented in Fig. 1. Finally, the line filter was positioned at 100 mm from the microchip where the near and far field profiles are illustrated in Fig. 6(d) and it is clearly evident from Fig. 6(d) that the output is Gaussian shaped and is

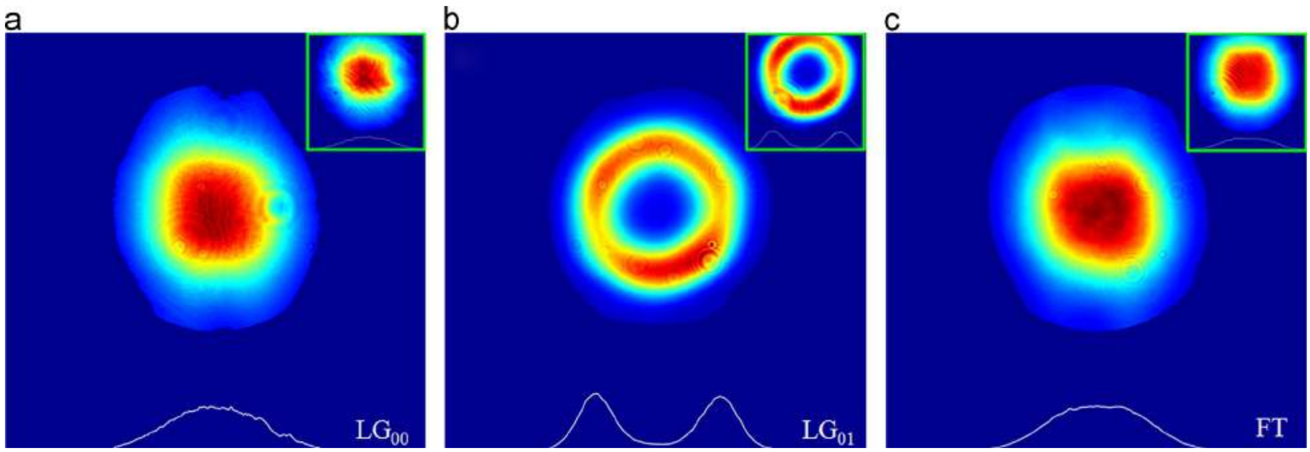

Fig. 5. The near field output of the MML cavity with no line filter is a (a) Gaussian beam (LG_{00}) indicating operation in the $L_{ext} > Z_R/2.5$ regime. The laser line filter acts as an external mirror (M_{ext}) where reflection of the output of the MML from the surface of the filter is directed back into the microchip thus creating optical feedback. With the line filter suitably positioned, operation in the $L_{ext} < Z_R/2.5$ and $L_{ext} \approx Z_R/2.5$ regimes, results in the near field outputs of a (b) donut-shaped beam and a (c) flat-top beam, respectively. The insets illustrate the respective far field profiles at the output.

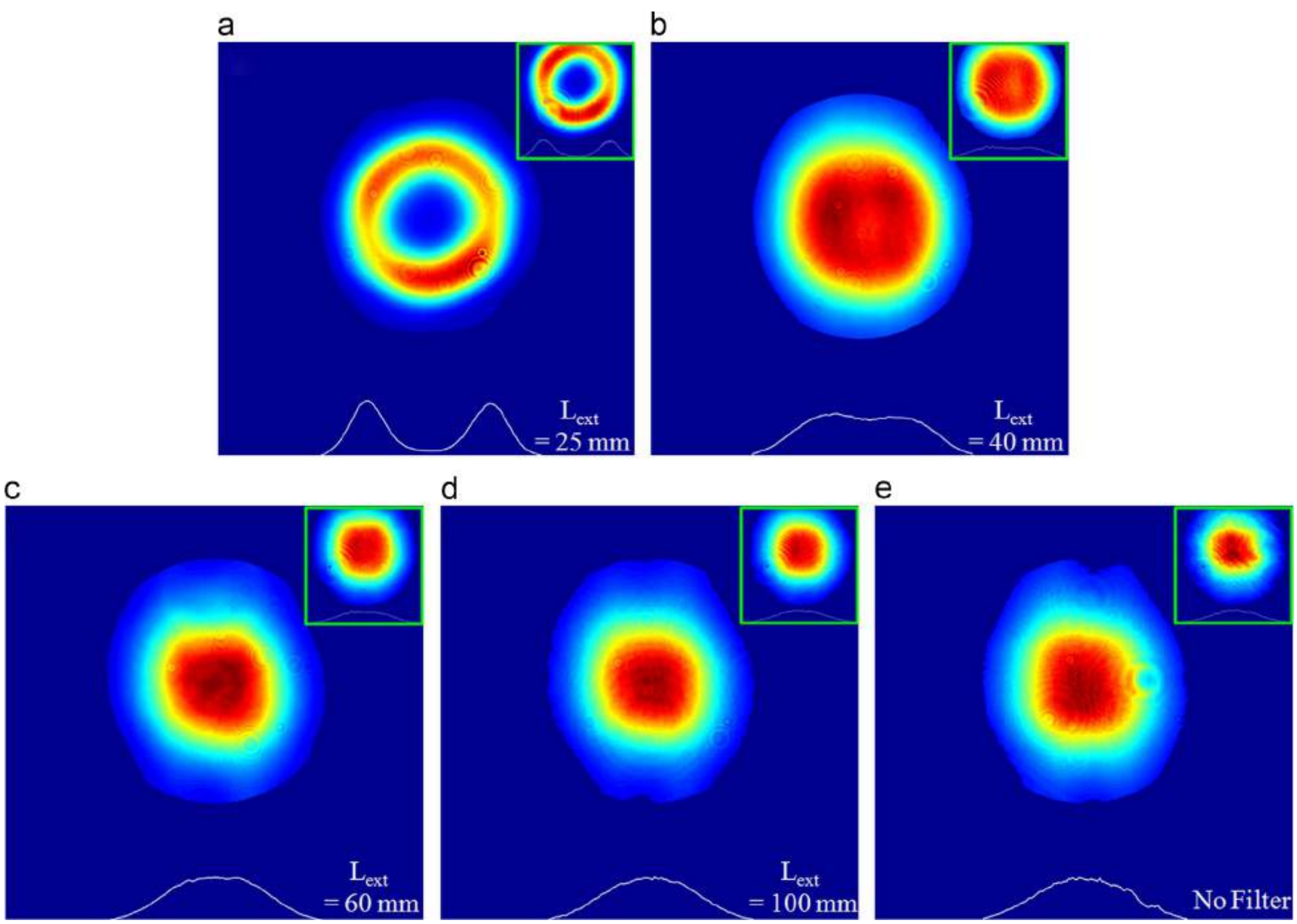

Fig. 6. The transition of the output from operation in the $L_{ext} < Z_R/2.5$ regime to the $L_{ext} > Z_R/2.5$ regime is determined by varying L_{ext} where we obtain in the near field a (a) donut-shaped output at L_{ext}=25 mm. At (b) L_{ext}=40 mm, the oscillation of the LG_{00} mode is established and begins to fill the hollow center of the donut-shaped mode. An increase of L_{ext} to (c) 60 mm presents a well defined flat-top beam in the near field that retains its transverse profile in the far field and indicates operation in the $L_{ext} \approx Z_R/2.5$ regime. With the line filter positioned at a distance of (d) 100 mm the near field output is a Gaussian beam where at this distance we arrive at an absolute limit to which the effects of the feedback occur and indicates operation in the $L_{ext} > Z_R/2.5$ regime. This compares well to the (e) MML operating without the effects of the line filter. The insets provided are the far field profiles at the output illustrating that the outputs are propagation invariant.

comparable to the output of the cavity with no line filter as shown in Fig. 6(e). Operation of the cavity under $L_{ext} = 100$ mm indicates that we are operating in the $L_{ext} > Z_R/2.5$ regime. The distance at which the filter is positioned is within a very narrow band to obtain a flat-top beam (approximately 50–70 mm) and with the filter positioned at 100 mm this provides an absolute limit as to which the effects of the feedback occur. The line filter has two surfaces which are distinguishable through their physical appearance in color where the one surface is silver and the other is green. For the effects of optical feedback the output from the microchip was incident on the silver surface, which distorted the output beam but aided the optical feedback.

4. Conclusion

We have demonstrated that it is possible to create structured light fields from a microchip laser by using an optical feedback technique. The excited medium emits light as an incoherent mix of spatially coherent modes. Using this approach we demonstrate the production of a Gaussian mode, a donut-shaped mode and a flat-top mode as the output. All three modes are propagation invariant and no custom optical elements are used to create them. This ushers in a new technique for creating miniature and tunable sources for structured light emission. Such tools would find immediately application in Stimulated Emission Depletion Microscopy (STED).

References

[1] F.M. Dickey, S.C. Holswade, D.L. Shealy, Laser Beam Shaping Applications, CRC Press Taylor&Francis, Boca Raton, 2006.
[2] L. Buratto, E. Bohm, Am. J. Ophthalmol. 143 (2007) 737.
[3] S.S. Bulanov, A. Brantov, V.Yu Bychenkov, V. Chvykov, G. Kalinchenko, T. Matsuoka, P. Rousseau, S. Reed, V. Yanovsky, D.W. Litzenberg, K. Krushelnick, A. Maksimchuk, Phys. Rev. E 78 (2008) 026412.
[4] D. Karnakis, J. Fieret, P.T. Rumsby, M.C. Gower, Proc. SPIE 4443 (2001) 150–158.
[5] F.M. Dickey, S.C. Holswade, Opt. Eng. 35 (1996) 3285.
[6] L.A. Romero, F.M. Dickey, J. Opt. Soc. Am. A 13 (1996) 751.
[7] J.A. Hoffnagle, C.M. Jefferson, Appl. Opt. 39 (2000) 5488.
[8] A. Laskin, V. Laskin, Proc. SPIE 8490 (2012) 84900J.
[9] B. Boubaha, D. Naidoo, T. Godin, M. Fromager, A. Forbes, K. Aït-Ameur, Appl. Opt. 52 (2013) 5766.
[10] S. Ngcobo, K. Aït-Ameur, I.A. Litvin, A. Hasnaoui, A. Forbes, Opt. Express 21 (2013) 21113.
[11] I.A. Litvin, A. Forbes, Opt. Express 17 (2009) 15891.
[12] W. Cheng, W. Han, Q. Zhan, Appl. Opt. 52 (2013) 4608.
[13] P.A. Bélanger, C. Paré, Opt. Lett. 16 (1991) 1057.
[14] P.A. Bélanger, R.L. Lachance, C. Paré, Opt. Lett. 17 (1992) 739.
[15] J.R. Leger, D. Chen, Z. Wang, Opt. Lett. 19 (1994) 108.
[16] I.A. Litvin, A. Forbes, Opt. Lett. 34 (2009) 2991.
[17] J.R. Leger, D. Chen, K. Dai, Opt. Lett. 19 (1994) 1976.
[18] J.C. Dainty, A.V. Koryabin, A.V. Kudryashov, Appl. Opt. 37 (1998) 4663.
[19] T.Y. Cherezova, L.N. Kaptsov, A.V. Kudryashov, Appl. Opt. 35 (1996) 2554.
[20] T.Y. Cherezova, S.S. Chesnokov, L.N. Kaptsov, V.V. Samarkin, A.V. Kudryashov, Appl. Opt. 40 (2001) 6026.
[21] M. Gerber, T. Graf, IEEE J. Quantum Electron. 40 (2004) 741.
[22] A.J. Caley, M.J. Thomson, J. Liu, A.J. Waddie, M.R. Taghizadeh, Opt. Express 15 (2007) 10699.
[23] J.J. Zayhowski, A. Mooradian, Opt. Lett. 14 (1989) 24.
[24] J.J. Zayhowski, Opt. Mater. 11 (1999) 255.
[25] D. Naidoo, T. Godin, M. Fromager, E. Cagniot, N. Passilly, A. Forbes, K. Aït-Ameur, Opt. Commun. 284 (2011) 5475.
[26] A. Forbes, Laser Beam Propagation: Generation and Propagation of Customized Light, CRC Press Taylor&Francis, Boca Raton, 2014.
[27] W. Cheng, W. Han, Q. Zhan, Appl. Opt. 52 (2013) 4608.
[28] W. Han, Y. Yang, W. Cheng, Q. Zhan, Opt. Express 21 (2013) 20692.
[29] A. Harfouche, K. Aït-Ameur, J. Opt. 15 (2013) 125702.
[30] K. Battou, K. Aït-Ameur, Opt. Commun. 183 (2000) 189.