2564

An Experimental Comparison of Linear and Parabolic Tapered Waveguide Lasers

S.J.Hettrick, J.Wang, C.Li, J.S.Wilkinson and D.P.Shepherd
Optoelectronics research Centre, University of Southampton, Highfield, Southampton, U.K..
dps@orc.soton.ac.uk

We compare the laser performance of linear and parabolic tapered waveguides in ion-exchanged Nd:glass, finding significant advantage for the linear guides, with demonstrated adiabatic expansion to widths of 250µm.

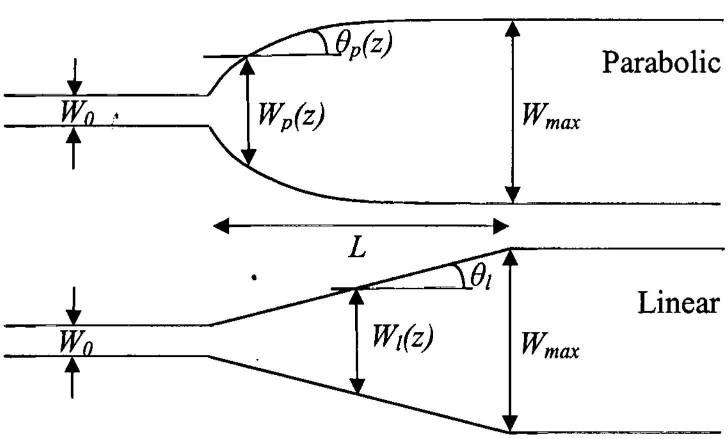
Keywords: waveguide lasers, tapers, ion-exchange

Introduction

Scaling the average power of diode-pumped integrated-optics laser sources requires the use of multimode waveguides to enable pumping by non-diffraction-limited high-power diode sources. However, a standard requirement for the integrated laser is that they give a single spatial mode, diffraction-limited output. One method of satisfying these opposing requirements is through the use of a structure that has a taper connecting a multimode, broad-stripe, planar section to a single-mode channel section of the waveguide [1-3]. The taper must be designed such that the fundamental mode propagating from the channel to the broad-stripe suffers minimal coupling to higher-order modes, as this power would be lost from the laser resonator when it returns through the taper to the channel. Several shapes for such tapers have been proposed [4] with the aim of expanding to as large an aperture in as short a length as possible. Here we experimentally compare the laser performance of linear and parabolic taper shapes opening to various widths of up to 250µm over lengths of up to 22mm.

Taper Design and Fabrication

Milton and Burns [4] proposed that considerations of diffraction and ray tracing suggest that a parabolic–shaped taper is a good design for low loss expansion, and they showed theoretically that tapers with an expansion coefficient $\alpha \leq 1$ (see figure 1) offer a reasonably adiabatic solution. Applying this design rule to a taper opening to 175µm in an ion-exchanged glass waveguide would



$$\theta_p(z) = \frac{\alpha\lambda}{2nW_p(z)} \qquad L \approx \frac{nW_{max}^2}{2\alpha\lambda}$$

$$W_p(z) = \sqrt{\frac{2\alpha\lambda z}{n} + W_0^2}$$

$$W_l(z) = \frac{W_{max} - W_0}{L} z + W_0$$

Figure 1 Parabolic and Linear Tapers

require a taper length of 22mm. However, our previous work on linear tapered waveguide lasers has shown that tapers produces by potassium-ion exchange through a mask opening up from 2.5µm to 175μm over just 12.5mm give an adiabatic expansion with no noticeable increase in propagation loss compared to standard channel waveguides fabricated on the same substrate [1]. Thus, in order to experimentally investigate the limits on the aperture size of parabolic and linear-shaped tapers we fabricated the tapers detailed in table 1, alongside standard channel waveguides, on the same substrate.

Table 1 Taper Design Parameters

Shape	W_{max}/μm	L/mm	α	θ_l / deg	Channel Length / mm	Total Length / mm
Linear	175	11	-	0.449	15	46
Parabolic	175	11	2	-	15	46
Linear	200	14.3	-	0.396	11.7	46
Parabolic	200	14.3	2	-	11.7	46
Linear	250	22.3	-	0.318	3.7	46
Parabolic	250	22.3	2	-	3.7	46

λ = 1.059μm, W_0 = 2.5μm, n = 1.515, broad-stripe length = 2cm

A 1.5-wt.% Nd_2O_3-doped BK7 borosilicate glass slab had one large face polished in preparation for the ion exchange process. A 250nm-thick aluminium film was deposited on the polished surface and standard photolithographic techniques were used to create openings in the film corresponding to the taper designs in table 1 and to simple 2.5μm-wide channels of the same length. The waveguides were then formed by immersion in molten potassium nitrate at 395°C for 12 hours. Finally, the substrate was end-polished to yield plane end-faces at 90° to the waveguide axis.

Laser Performance Characterisation

The laser performance of the tapers and channels was investigated by pumping the channel end of the waveguide with a Ti:sapphire laser tuned to the Nd^{3+} absorption at 807nm. The laser

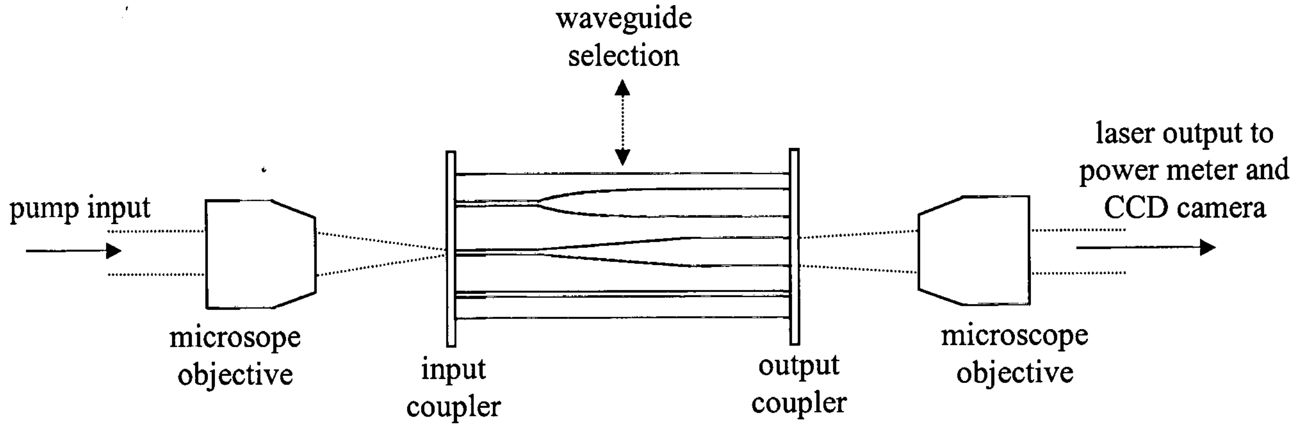


Figure 2 Experimental Set-Up

resonator was formed by butting thin mirrors to the plane end-faces of the waveguide substrate, using a thin film of fluorinated liquid to aid adhesion. The input mirror was highly reflecting at the lasing wavelength of 1.059μm and had 95% transmission at the pump wavelength. The output coupler had a reflectivity, R, of 80% at the lasing wavelength and was highly reflective at the pump wavelength such that the absorption of the launched pump power is effectively 100%. The experimental set-up is shown schematically in figure 2 and the thresholds and slope efficiencies obtained are tabulated in table 2.

Table 2 Laser Performance

Shape	W_{max} / μm	Threshold Power / mW	Slope Efficiency / %
linear	175	40	18
linear	200	35	21
linear	250	42	19
parabolic	175	34	23
parabolic	200	55	11
parabolic	250	115	5
channel	2.5	27	22

As an example, the spatial profiles for the output of the 200μm-wide tapers, captured by imaging the outputs onto a CCD camera, are shown in figure 3.

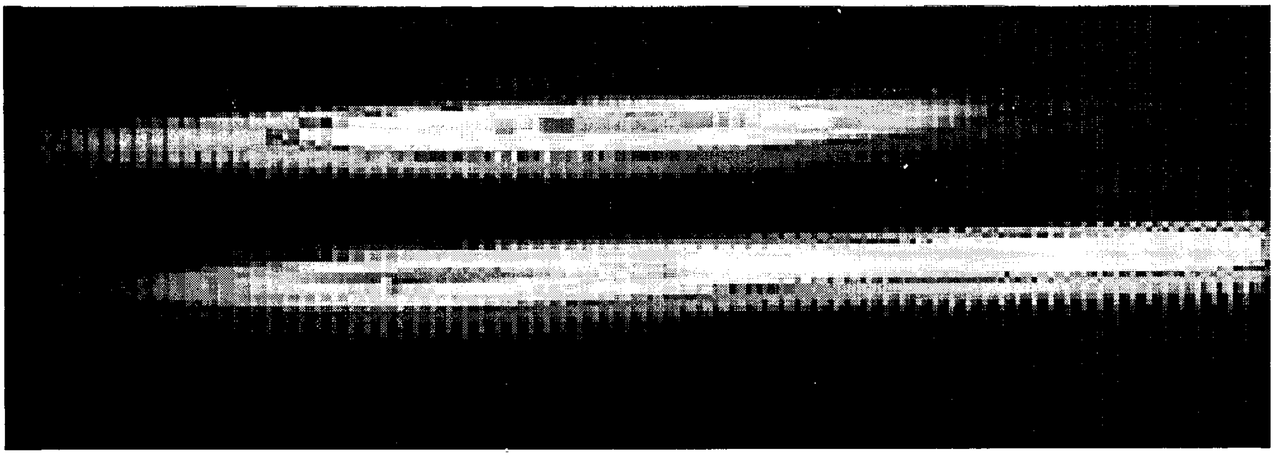


Figure 3 Imaged mode profiles for the 200μm-wide linear (upper) and parabolic (lower) tapers

Discussion

It can be seen from table 2 that, within experimental error, the slope efficiency of all the linear tapers is comparable to that of the channel guide, indicating that there is no significant increase in propagation loss due to the taper for the aperture sizes investigated here. The maximum possible slope efficiency (assuming a spatial overlap of 1) is given by [5]

$$\eta_{\max} = \frac{\lambda_p}{\lambda_s}\left(\frac{-\ln R}{-\ln R + \delta}\right),$$

where λ_p and λ_s are the pump and laser wavelengths, and δ is the round-trip loss exponent. Using this equation a maximum possible loss of 0.25dB/cm is obtained, which is a typical background propagation loss for ion-exchanged waveguide of this type. The low loss indicates an adiabatic expansion of the fundamental mode in the taper and this is confirmed by the observation of clean Gaussian output profile, as shown in figure 3.

In contrast, it can be seen that the performance of the parabolic tapers is comparable to that of the linear tapers and channel guide for the 175μm-wide aperture, but the performance gets considerably worse for the larger apertures. At 250μm the additional round-trip loss, over the 0.25dB/cm background loss, is as high as 11dB. The output spatial profiles of the larger parabolic tapers display a distinctly multimode nature, as shown in figure 3.

Summary

The performance of linear and parabolic tapers with fast expansion rates (α=2) to apertures of up to 250μm has been compared. The linear tapers show no significant additional losses over the background propagation loss of the ion-exchanged waveguide for the range of apertures investigated here, whereas parabolic tapers of the same length show a significant drop-off in performance for the larger aperture sizes. The large losses found for the parabolic tapered waveguide laser resonator were confirmed by the qualitative observation of higher-order modes in the spatial profile of the output from the broad-stripe region. These results suggest that linear tapers are compatible with high-average-power pumping by broad-stripe diode lasers and should allow integrated lasers with powers at the Watt level.

[1] S.J.Hettrick, J.I.Mackenzie, R.D.Harris, J.S.Wilkinson, D.P.Shepherd, A.C.Tropper, *Opt. Lett.* **25**, 1433-1435, 2000.

[2] T.Tamanuki, T.Sasaki, M.Kitamura, *Opt. Quantum Electron.* **28**, 513-517, 1996.

[3] J.D.Minelly, L.A.Zenteno, M.J.Dejneka, W.J.Miller, D.V.Kukzenkov, M.K.Davis, S.G.Crigler, M.E.Bardo, *Digest of Optical Fiber Communications Conference*, paper PD2-1, 2000.

[4] A.F.Milton, W.K.Burns, *IEEE J. Quantum Electron.* **QE-13**, 828-835, 1977.

[5] W.P.Risk, *J.Opt. Soc. Am.* **5**, 1412-1423, 1988.