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Ion-Exchanged Tapered Waveguide Laser in Neodymium-Doped BK7 Glass

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Abstract

We report the first operation of a planar dielectric tapered waveguide laser. The waveguide lasers are fabricated by potassium ion-exchange in Nd^{3+}-doped BK7 glass, and consist of a single-mode channel waveguide of a few microns width followed by a linear taper up to a broad region with a width of ~180μm. A slope efficiency of 42% is found in both the tapers and standard channel waveguides fabricated on the same substrate, indicating similar internal losses and hence the low-loss nature of the tapered beam expansion. The output from either end of the tapered structure is found to be near to diffraction-limited.

There is a growing requirement for high-average-power, diffraction-limited sources for industrial, military, medical and research applications. Ideally these sources should also be compact, efficient and robust. This has motivated research in both diode lasers, and diode-pumped solid-state lasers. Semiconductor laser systems have so far been limited in the amount of diffraction-limited output power they can produce (<10W) due to thermal loading and damage considerations. However high-power, non-diffraction-limited diodes can be used to pump resonators based on rare-earth-doped laser crystal gain elements, such as Nd:YAG, which can produce near-diffraction-limited outputs at very high average powers (~100W). Nevertheless, the need to pump another laser resonator necessarily adds complication to the optical system, especially if beam-shaping of the highly-asymmetric output of a diode-bar is required. This has led to recent work on high-average-power planar waveguide lasers [1] as the planar geometry is naturally compatible with that of a diode-bar pump laser, allowing very compact coupling schemes, as well as being ideal for thermal management [2]. Very simple and efficient diode-to-waveguide coupling systems have recently been demonstrated based on a fibre/rod lens system [3] and by proximity coupling [4]. The multi-Watt waveguide lasers demonstrated in this way have been based on planar guides with a broad gain region and a monolithic plane/plane resonator design. This has inevitably led to a multi-mode, non-diffraction-limited output in the non-guided direction. Therefore the use of a tapered waveguide to couple the broad diode-pumped gain region to a single-mode channel region in order to obtain a diffraction-limited output is of great interest.

The concept of using tapered waveguides to couple from broad to narrow channel waveguides is well established and various designs for adiabatic expansion of the lowest-order spatial mode of a channel waveguide have been described [5]. Tapered waveguides have been employed in diode-laser systems in an attempt to produce high-power, low-divergence, diffraction-limited outputs [6], although these are often used as power amplifiers to avoid facet damage caused by having high average powers in the small channel section. Indeed, these amplifiers are often simply a flared gain region rather than an actual tapered waveguide [7]. However, the adiabatic tapered waveguide should be applicable to dielectric planar waveguide laser resonators due to their high power-handling capability. Milton and Burns [5] have shown that a parabolic shaped taper can give a low-loss expansion to a width, W, if the length, L, satisfies the following condition,

$$L \geq \frac{W^2 n_m}{2\lambda} \tag{1}$$

where n_m is the mode index, λ is the free-space wavelength, and the initial channel width is much smaller than W. Thus for a 1.06μm mode in BK7 glass (n_m~1.5), a 200μm width can be reached in 3cm. However, to increase the width further to the point where end-pumping with a diode-bar becomes feasible, W~5mm, would require a length of 18m. The practicalities of planar fabrication and the expected values of propagation loss (0.1 - 1 dB/cm) restrict the maximum length to ~10cm. Nevertheless, a width of a few hundred microns is compatible with high-brightness broad stripe diode pumping, which could lead to lasers of around ~1W output. For diode-bar pumping, a side-pumped geometry can be envisaged although a material with a very strong absorption of the diode pump light, such as $Nd:YVO_4$, would be required.

Here we demonstrate, for the first time to our knowledge, a tapered planar dielectric waveguide laser. We choose the well-established fabrication technique of potassium ion-exchange [8], and make simple linear tapers in Nd^{3+}-doped BK7 glass. Standard channel waveguides are also made on the same substrate for the sake of comparison, enabling estimation of the additional losses due to the taper.

The 1.5wt.% Nd_2O_3 doped laser host was prepared from commercially available BK7 borosilicate glass and is the same as that investigated in detail in ref.[9]. A 30 by 20 by 2mm substrate was cut from the doped glass and one large face was polished in preparation for the 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 both standard 2.5μm-wide channels and 2.5μm-wide channels with a 12.5mm-long linear taper section opening out to a 175μm-wide region. Ion-exchanged waveguides were then formed through these openings by immersing the substrates in molten potassium nitrate at 395°C for 12 hours. Finally, the substrate was end-polished to give plane end-faces at 90° to the waveguide axis, leaving a 24mm long structure which has approximately equal length narrow and broad sections of ~6mm. The parameters for the ion-exchange process were chosen so as to give a waveguide that has just a single mode at 1.06μm in the narrow channel section, thereby ensuring a high-quality spatial output from this end of the waveguide. This calculation was based upon an expected waveguide index profile of the form [8],

$$n(x,y) = n_s + \Delta n \exp\left(\frac{-x^2}{d_x^2}\right) \operatorname{erfc}\left(\frac{y}{d_y}\right) \qquad y \geq 0 \qquad (2)$$

where n_s is the substrate refractive index (1.50669 at 1.06μm [10]) and the parameters Δn (0.0092 and 0.0080 for the TM and TE polarisations respectively) , d_x (4.8μm) and d_y (4.0μm) are estimated for our fabrication conditions using the work of Weiss and Srivastava [8]. These parameters, apart from n_s, were assumed not to change significantly from there value at 633nm.

It should be noted that we have ignored any overall change in refractive index due to the Nd doping. The corresponding modal properties of the channel section of the waveguide were calculated using a commercial software package (BBV Selene Pro) based on the effective index method. The tapers used here are not expected to be the optimum design for an adiabatic expansion, being linear in shape and with too fast an expansion to satisfy eqn.(1). However, they represent a simple first step in our investigation of the lasing behaviour of such tapers.

A tunable Ti-sapphire laser was used as the pump source for the waveguide laser experiments. The beam was launched into the narrow channel end of the taper using a X10 objective and an efficiency of 78% was calculated from transmission measurements with the Ti-sapphire tuned off the Nd^{3+} absorption. The resonator was formed by placing thin, light-weight, mirrors against the polished end-faces and holding them in place with the surface tension of a small amount of fluorinated liquid. The input mirror was highly reflecting (HR) at the lasing wavelength (~1.06μm) and had high transmission (87%) at the pump wavelength (~808nm). The output mirror was either another HR or a 20% transmission output coupler. The output was collected with a X10 objective and directed towards the power meter or other diagnostic equipment as appropriate. Figure 1 shows the lasing characteristics obtained with the 20% output coupler from the taper and from a standard channel waveguide on the same substrate. Almost identical slope efficiencies of 42% are obtained from both guides. The taper shows a higher absorbed power threshold of 15mW compared to 5mW for the channel. Using two HR mirrors the thresholds were 3mW and 5mW of absorbed power for the channel and tapered waveguide respectively. The maximum possible slope efficiency using this output coupler (assuming a spatial overlap of 1) is given by [11],

$$\eta_{max} = \frac{\lambda_p}{\lambda_s}\left(\frac{-lnR}{-lnR+L}\right) \quad (3)$$

where λ_p and λ_s are the pump and signal wavelengths, R is the output coupler reflectivity, and L accounts for any other round-trip loss. This implies that an upper limit of 18% (0.8dB) can be placed on the round-trip loss in both cavities. This figure is consistent with the losses being dominated by a propagation loss of <0.2dB/cm. It is clear from these results that the cavity loss for the tapered waveguide is not significantly increased from that of the standard channel guide. The small increase in threshold may be related to the larger area being pumped in the tapered guide as a significant portion of the pump light will penetrate beyond the initial 6mm-long channel section into the taper (the expected 1/e pump absorption length is 8mm). The channel waveguide lasers were predominantly TE polarised as previously observed [12], however the tapers lased in the TM polarisation. The output spectrum was similar in both cases consisting of a broad lasing band from 1055nm to 1062nm, with peaks at 1056.6nm, 1058.7nm and 1061.0nm. This is again similar to previously reported behaviour [12].

The low-loss nature of the taper suggests that there is little coupling from the fundamental mode to higher-order modes in the taper, that cannot be supported in the narrow channel section. To confirm this, the outputs of the taper and channel waveguides were investigated using both a CCD camera and a Coherent Modemaster M^2 meter. Figure 2 shows typical intensity profiles for the outputs of the taper and channel respectively. It can be seen that both appear to be single-lobed but, as expected, with different degrees of asymmetry. The output mode of the taper appears to be approximately 6 times wider than that of the channel. Measurements of the M^2 value confirmed the near-diffraction-limited nature of the taper output with values of ~1.5 being obtained in both the vertical and horizontal planes, while the channel guide gave output M^2 values of 1.2 and 1.0 in the two planes. We have also pumped the tapered waveguide lasers from the broad end, as would be the case with broad stripe diode pumping, and have observed similar laser performance apart from a slightly higher threshold of 10mW of absorbed power for two HR mirrors, due to the larger pumped area. We also observed an improved output M^2 of 1.1 by 1.0 as the output is now obtained from the narrow channel end. It therefore appears that, despite the simple linear taper design, a near adiabatic expansion has been achieved. Modelling of the tapers was carried out using a commercially available software package (BBV Prometheus) and was based on a two-dimensional, wide angle, finite difference beam propagation method. An example of the predicted behaviour is shown in figure 3 where a double pass through the structure is modelled using two back-to-back tapers and the TM_{00} mode of the channel section as the start field. This figure demonstrates that loss incurred by the taper is due to the generation of higher order modes which cannot be supported by the channel and that this loss process mainly occurs as the beam is re-focussed into the channel after the second pass of the taper. However, it can also be seen that this approximate calculation predicts a much larger loss than was observed in practice, suggesting that a full three-dimensional analysis which accounts for the graded index nature of the waveguide in the x direction is required.

In summary, we have demonstrated the first use of a tapered waveguide in a planar dielectric geometry. The Nd^{3+}-doped BK7 laser had a threshold of 15mW and a slope efficiency of 42% for a 20% output coupler when end-pumped by a Ti:Sapphire laser. Over 100mW of TM polarised laser output was obtained in this way. The laser results suggest that the taper causes negligible extra propagation loss and the output is seen to be near to diffraction-limited. Such waveguides are expected to be compatible with broad stripe diode-pumping leading to compact efficient lasers with good spatial output around the 1W level. Further work is required to fully optimise the taper design for optimum laser performance. This could include the use of a parabolic taper and investigation of a side-pumped geometry that would allow the use of diode-bar pump lasers.

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Figure Captions

Figure 1 Output power versus absorbed pump power for the channel and tapered waveguide laser using a 20% output coupler.

Figure 2 Imaged spatial profiles of the output of the channel and tapered waveguide lasers, as viewed on a CCD camera. The dimensions correspond to those observed at the camera.

Figure 3 Theoretical propagation in one round-trip of the laser cavity for the TM_{00} mode. The ten lowest order modes are calculated and summed to give the total guided power. The figure above the graph represents the double pass of the tapered structure occurring in one cavity round-trip.

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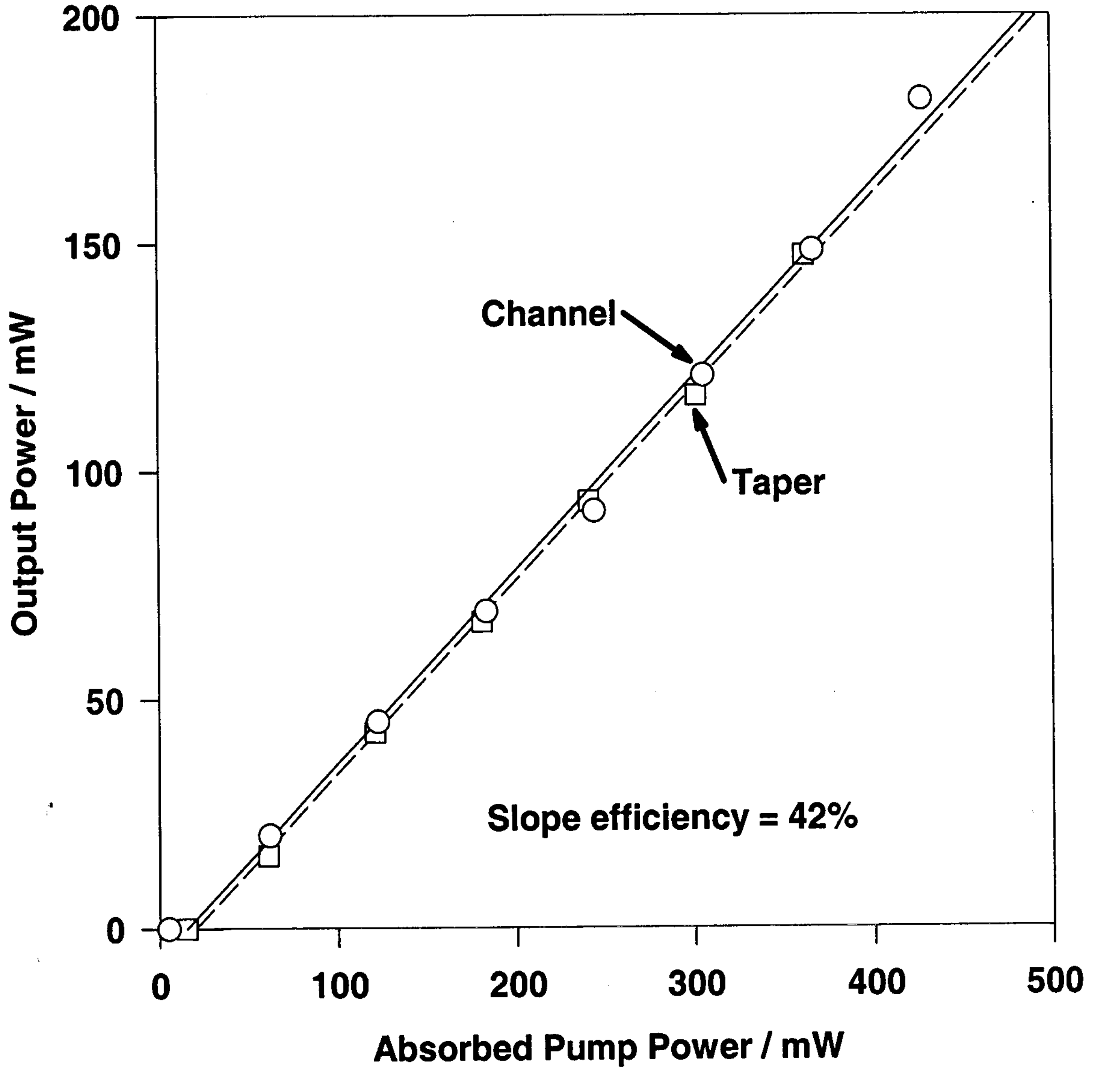
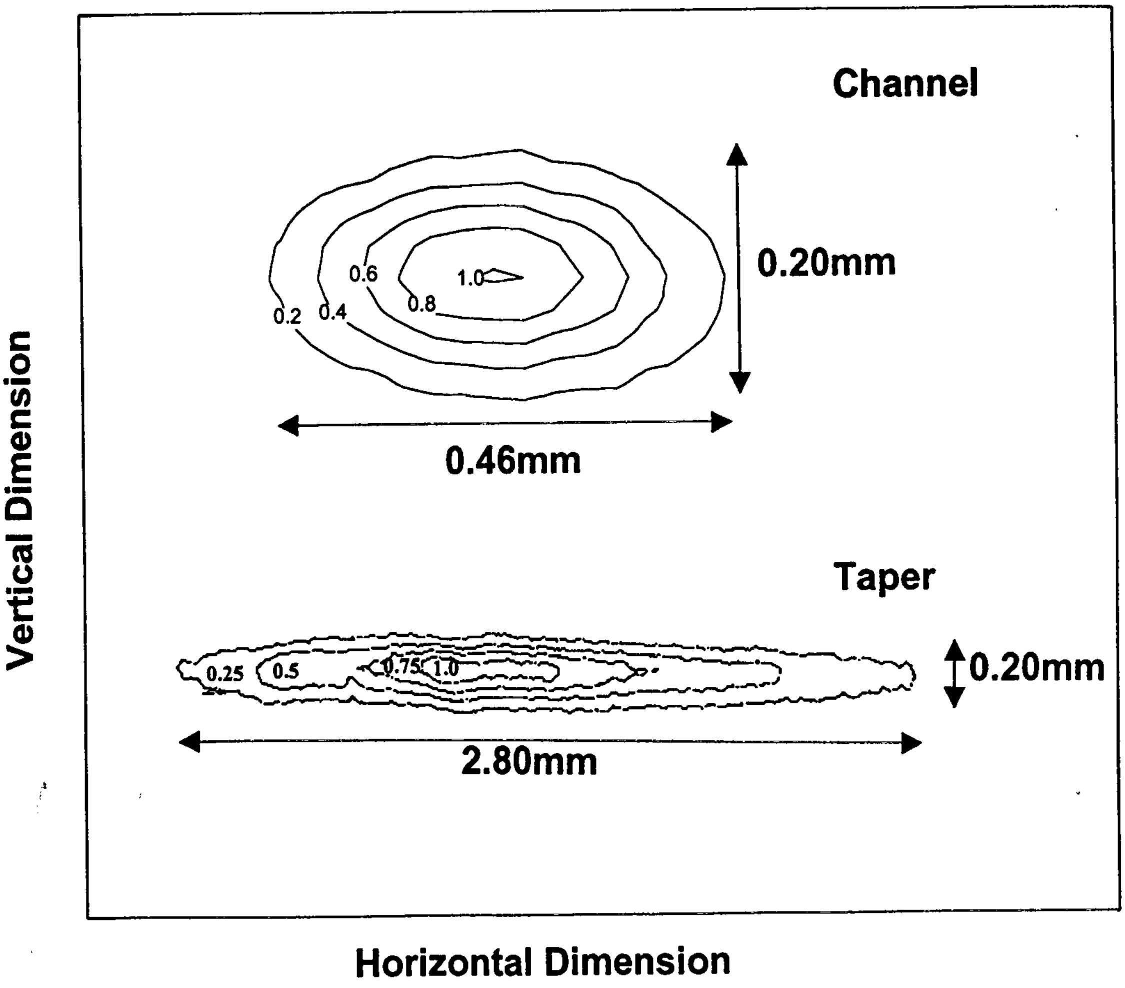
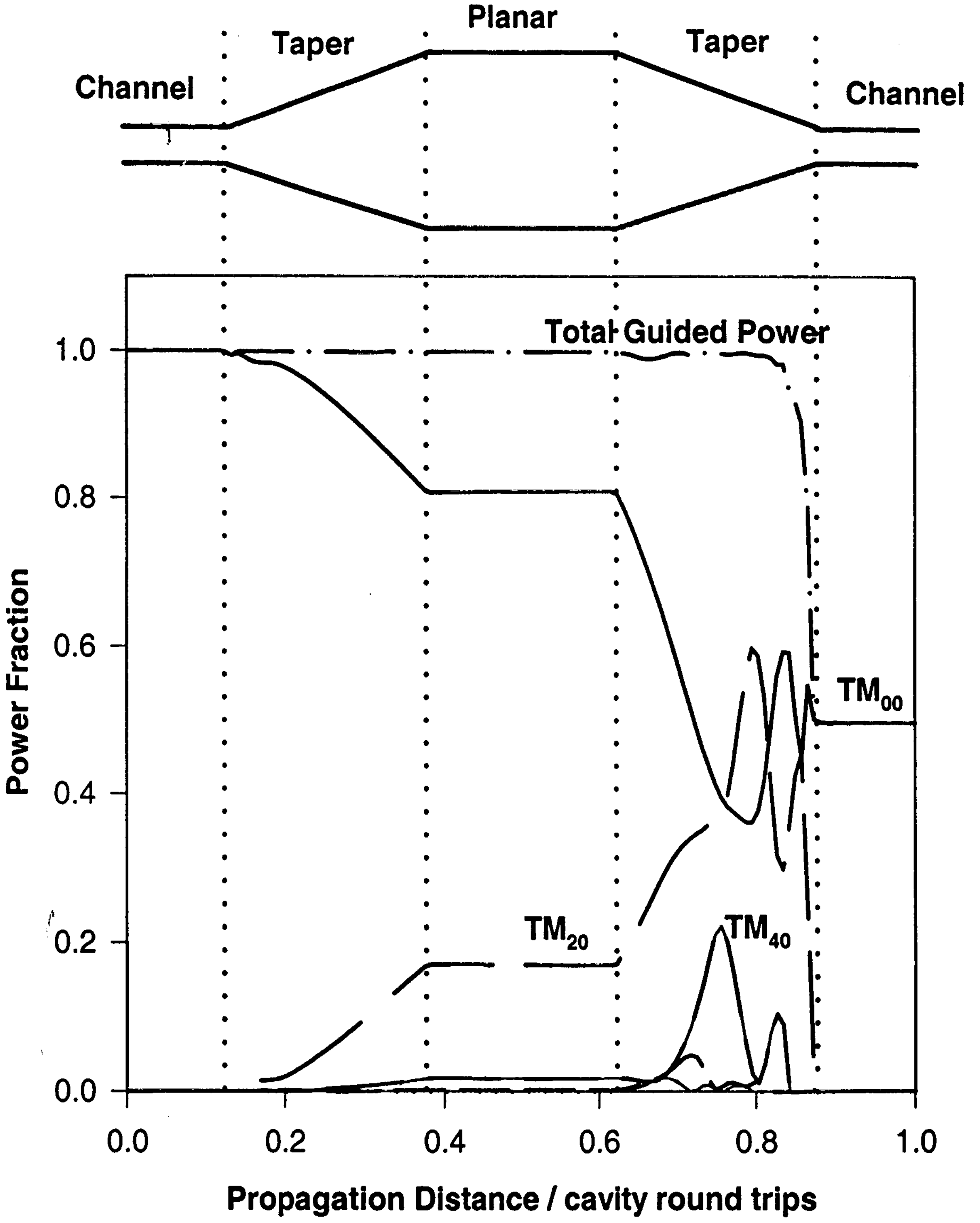


200
150
100
50
0
Output Power / mW
Channel
Taper
Slope efficiency = 42%
0
100
200
300
400
500
Absorbed Pump Power / mW



Channel
0.20mm
0.46mm
0.2
0.4
0.6
0.8
1.0
Taper
0.20mm
2.80mm
0.25
0.5
0.75
1.0
Vertical Dimension
Horizontal Dimension



Planar
Taper
Taper
Channel
Channel
Total Guided Power
1.0
0.8
0.6
0.4
0.2
0.0
Power Fraction
TM_{00}
TM_{20}
TM_{40}
0.0
0.2
0.4
0.6
0.8
1.0
Propagation Distance / cavity round trips