A polarised, brightness-enhanced Nd:$Y_3Al_5O_{12}$ planar waveguide laser

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Abstract

A simple method for the production of a polarised Nd:$Y_3Al_5O_{12}$on $Y_3Al_5O_{12}$ planar waveguide laser is reported. A 50nm layer of Au deposited on the surface of an unclad, 8.3 µm thick core region has produced an improvement in the TE/TM polarisation extinction ratio from 7dB to 27dB. The M^2 of the beam in the guided plane has been reduced from 1.53 ±0.04 in an uncoated region of the waveguide to 1.17 ±0.01 in the Au coated region using optimum pump launch conditions.

Laser devices based on a planar waveguide geometry hold out the prospect of a compact, high-power visible light source by the combination of an active gain region and a non-linear waveguide. However, in order to pump effectively the non-linear region, a polarised output from the waveguide laser is required. Nd:$Y_3Al_5O_{12}$ (Nd:YAG) provides an attractive choice for the gain medium, however due to its isotropic nature, the laser output is unpolarised. In this letter we present a very simple technique for obtaining a linearly polarised, transverse electric field (TE) output which when combined with recently obtained diode-bar pumped planar waveguide results [1] could offer a route to a high-power polarised planar waveguide laser. The method demonstrated also gives the significant benefit of improving the beam quality parameter (M^2) of the output beam in the guided direction. This should allow brighter outputs from such a device than could otherwise be obtained.

One straightforward mechanism for controlling modal losses in waveguide structures is to coat the waveguide with a thin metal film [2]. The transverse magnetic field (TM) modes of the waveguide penetrate more deeply into the metal layer resulting in higher losses for the TM modes compared to the TE modes. In addition, our calculations show that a surface plasmon mode should be excited for the TM modes resulting in enhanced coupling into the metallic film. A surface plasmon is a TM mode guided by the interface between two media whose dielectric constants have real parts of opposite sign. In the visible and infra-red part of the electromagnetic spectrum this requirement can be fulfilled by a dielectric and a metal. Under these conditions TE polarised light will not excite a surface plasmon mode and will, in our case, see reduced propagation losses compared to the TM polarisation.

If we consider an unpolarised multimode slab waveguide system which guides both TE and TM modes, coated with a thin metal film, then operation of the coated waveguide can be reasonably described in terms of coupled modes [3]. The TM modes couple to the surface plasmon mode. The strength of this coupling depends on how closely phase-matched a given TM mode is to the surface plasmon mode. This coupling of TM polarised light out of the dielectric waveguide into the lossy surface plasmon mode increases the losses of the TM modes leading to preferential TE laser operation. In a multimode waveguide device, the evanescent part of the laser mode extends further into a surface layer for higher order modes than for the fundamental. Thus the TE polarised modes have increasing propagation losses as the mode number increases resulting in a device which has lowest propagation losses for the fundamental mode in the TE polarisation.

In order to verify this principle we carried out modelling for an 8.3 µm planar waveguide with a 50nm gold coating. The waveguide modelled was chosen to match a waveguide available for subsequent experiments. This waveguide was fabricated by liquid phase (LPE) epitaxy and consisted of an 8.3 µm thick core region of 1at%

Nd, 5at% Ga, 12at% Lu doped YAG (n=1.82923) on a 500 µm thick undoped YAG substrate (n=1.81523). The waveguide had no cladding layer allowing direct metallic coating of the surface of the core region. The Ga in the core increases the refractive index of the core region relative to the undoped substrate on which the core is grown. The Lu is included to compensate for the large size of the Ga ions and allow epitaxial growth [4].

The waveguide model uses a transfer matrix approach to evaluate numerically the eigenvalue equation of a given multilayer waveguide system. Once the characteristic eigenvalue equation has been determined from the system transfer matrix, the model employs the argument principle method (APM) to count rigorously and locate the roots to the TE and TM modal eigenvalue equations. The APM relates the number of zeros of an analytical function to a contour integral in the complex plane. In this case, the analytical function is the eigenvalue equation and the complex plane is that of modal dispersion and absorption. When the number of roots to the eigenvalue equation is known, the model locates them using Muller's complex root finding technique [5].

Mode number	TE Loss dB/cm	TM Loss dB/cm
0	0.093	1.72
1	0.366	6.47
2	0.693	12.89
3	0.790	

Table 1 Predicted propagation losses in dB/cm for the 4 TE and 3 TM modes supported by an 8.3µm thick Nd:$Y_3Al_50_{12}$ on $Y_3AI_50_{12}$ waveguide with a 50nm thick Au cladding layer for a propagation wavelength of 1.06µm.

Our model revealed that an uncoated waveguide would support 4 TE and 4 TM modes reducing to 4 TE and 3 TM modes once the gold coating was included. Calculated propagation losses for the modes are shown in table 1 at the lasing wavelength of 1.06 µm. Figure 1 shows the calculated field for the TM, mode in the region near the surface of the device. The increase of the field towards the boundary between the waveguide core and the Au film demonstrates the effect of the surface plasmon on this mode. This interaction results in increased coupling into the lossy Au film

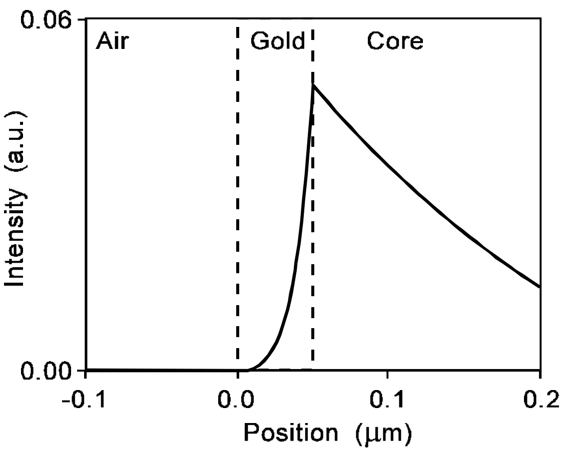

Figure 1. Calculated magnetic field intensity profile in the surface region for the TM_1 mode of an 8.31 µm thick Nd:Ga:Lu:$Y_3Al_50_{12}$ on $Y_3Al_50_{12}$ waveguide with a 50nm Au layer deposited on the surface. This plot shows that the coupling of the mode from the waveguide core into the lossy surface film has been enhanced due to the effect of a surface plasmon interaction.

and therefore produces enhanced propagation losses for this mode. The additional 0.1 dB/cm loss induced by the Au film for the fundamental TE mode is similar to the estimated propagation loss of <0.1dB/cm for the unclad waveguide [6]. With this simple single layer design we would not expect a dramatic difference in the losses for the pump and laser wavelengths.

The experimental investigation was carried out using the waveguide described above which was thoroughly cleaned and then coated with 50nm of Au using an Edwards thermal evaporator. The gold coating was etched from one half of the sample to allow easy comparison between coated and uncoated regions. The endfaces of the waveguide were also etched to remove any gold which had coated these areas during the deposition.

In order to determine the lasing behaviour of this sample we used a Ti:Al_2O_3 laser, operating around 800nm in the TE polarisation, to excite the Nd^{3+} ions. Lasing occurred on the four-level, $^4F_{3/2} \rightarrow {}^4I_{11/2}$, transition around 1.06 µm using the experimental arrangement illustrated in figure 2. Where required, laser mirrors were attached to the endfaces of the waveguide by the use of the surface tension of a thin layer of fluorinated liquid. The adhesion of the mirrors was, in some cases, improved by gluing the edges of the mirrors to the waveguide substrate. Detection of the laser signal was provided either by a large area Si detector or, where power measurements were taken, a Newport 840 optical power meter. One method of characterising the beam quality of a laser is by means of measurement of the M^2 parameter [7]

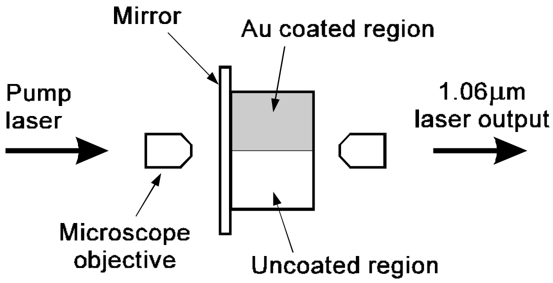

Figure 2. Plan view of arrangement used for laser experiments on the Au-coated waveguide device.

which was obtained for the output from our device using a Coherent Modemaster M^2 meter.

Initially, the pump light was end-launched into the waveguide with a X5 microscope objective. With optical feedback provided by a highly reflecting mirror at 1.06 μm (high transmission at 800nm) on one endface of the waveguide and the Fresnel reflection (~9%) from the other endface, lasing was obtained in both the coated and uncoated regions. The laser threshold in the two regions was similar (~140mW) demonstrating no large increase in the guide propagation losses caused by the gold film. Exact comparison of propagation losses and laser performance between different regions of the device is difficult due to the formation of a Fabry-Perot etalon between the endface of the waveguide and the mirror resulting in slightly different laser cavities.

The output polarisation was then examined using a Glan-Thompson polariser. The uncoated region has both TE and TM components, whereas the output from the Au coated region exhibits near-linearly polarised TE output. Indeed if we define an extinction ratio as P_{max}/P_{min} where P_{max} and P_{min} are the maximum and minimum powers obtained as the polariser is rotated, the extinction ratio improved from 7dB in the uncoated region to 27dB in the Au coated area.

The output from the waveguide laser was collimated using a 25mm focal length cylindrical lens in the guided direction and a 200mm cylindrical lens in the unguided direction. The M^2 of the beam in the guided direction was then determined. To quantify this result accurately, the M^2 was measured at 5 separate locations in both the coated and uncoated regions allowing an average value with its associated standard error to be found. In the uncoated region, the M^2 of the beam in the guided direction was found to be 1.53 ±0.04. Under the Au film, the M^2 was 1.17 ±0.01. In order to examine this behaviour further we launched the pump light into the waveguide using a X16 microscope objective to deliberately excite the higher order guided modes. In this case, the M^2 of the laser output in the uncoated region was found to be 2.8 ±0.5, compared to a value of only 1.24 ±0.05 in the coated region. These results represent a significant improvement in beam quality of the device and indicate that the Au film is inducing losses in the higher order TE modes, without significantly affecting the fundamental mode, as expected from the modelling carried out on this system.

In conclusion, we have demonstrated a Nd^{3+} doped $Y_3Al_5O_{12}$ waveguide with integrated polarisation control obtained simply by coating the device with a thin Au film. While the polarising effects of metal films are well known, we believe that this is the first time that such a technique has been used to control the polarisation of a planar waveguide laser. Furthermore, the Au has also induced extra propagation losses for the higher order TE modes which has resulted in a significant improvement in the beam quality of the device. This should allow us to produce a multimode waveguide which is thick enough, and has a high enough numerical aperture to allow efficient diode-bar pumping but which has near single mode laser output in the guided direction. In order to obtain such performance, we plan to coat only that region in the device that falls after the pump has been substantially absorbed so as to avoid loss of pump power. We believe that the benefits in terms of polarised laser output and enhanced brightness from such a device will compensate for the small increase in cavity losses. We also plan to investigate the use of other metals as the coating. Modelling studies have shown Cu to be a promising candidate for enhanced performance, although technical issues such as the possible poor adhesion of this material and its long term chemical stability will have to be addressed.

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