reabsorptions by U^{4+} ions. In our view, these two facts explain the CW functioning at room temperature of the U^{3+} laser.

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Single-frequency Er^{3+}-doped silica-based planar waveguide laser with integrated photo-imprinted Bragg reflectors

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Indexing terms: Optical waveguides, Gratings in fibres, Fibre lasers

Single-longitudinal-mode operation of Er^{3+}-P_2O_5-codoped silica planar waveguide lasers which are equipped with integrated Bragg grating reflectors is demonstrated, with a polarised output of 340μW at 1546nm. The gratings are photo-imprinted using 193nm light exposure through a phase mask in GeO_2-free optical waveguides that have been sensitised by H_2 loading.

Wavelength-controllable single-longitudinal-mode lasers are important for wavelength-division-multiplexing (WDM) optical communication systems. Er^{3+}-doped fibre lasers equipped with in-fibre distributed Bragg reflectors (DBRs) are promising because they operate with narrow linewidths and without mode hopping in the 1.5μm transmission window [1, 2]. The DBR fibre lasers use the narrowband reflection of Bragg reflectors in order to select only one longitudinal oscillation mode of the cavity. The DBRs have been fabricated by UV exposure in Er^{3+}-doped fibres using the photosensitivity of GeO_2-doped silica [3].

The formation of single-frequency lasers in planar waveguides is required in order to permit the integration of wavelength-controlled optical sources with passive waveguide devices. As a first step toward the development of such integrated optical circuits, it is essential to demonstrate singlemode operation of planar waveguide DBR lasers. Singlemode oscillation at 1.05μm has been reported in an Nd^{3+}-doped glass ion-exchanged waveguide with a relief-type DBR [4].

In this Letter, we report single-frequency Er^{3+}-P_2O_5-codoped silica planar waveguide lasers with integrated photo-imprinted DBRs [5]. The technique for photo-imprinting DBRs in Er^{3+}-P_2O_5-codoped silica waveguides, which is GeO_2-free, and the lasing characteristics of the waveguide DBR lasers are described.

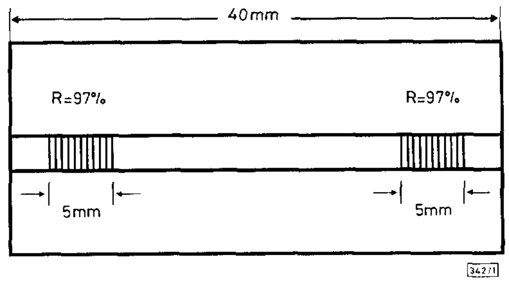

Fig. 1 *Configuration of Er^{3+}-doped planar waveguide laser with integrated distributed Bragg reflectors*

Two singlemode lasers with photo-imprinted DBRs were fabricated in Er^{3+}-doped silica-based waveguides on silicon substrates. Fig. 1 shows the configuration of the waveguide lasers. The waveguides, which were fabricated by flame hydrolysis deposition and reactive ion etching [6], had an 8 × 7μm Er^{3+}-P_2O_5-SiO_2 core with a refractive index 1.2% greater than that of the silica cladding. The 0.5wt%-Er^{3+}-doped waveguides showed a saturated gain of 0.3dB/cm at a wavelength of 1546nm. The polarisation dependence of the gain was less than 0.03dB/cm, a value which corresponds to the measurement accuracy for the gain. To photo-imprint DBRs, we require the P_2O_5-doped silica to be photosensitive. Recently, we demonstrated that a large refractive index change of more than 10^{-4} is photo-induced in P_2O_5-doped silica that is sensitised by H_2 loading or flame brushing prior to exposure to 193nm light [5]. In this work, the DBRs were formed in the Er^{3+}-doped waveguides using a similar procedure. The waveguides were immersed in H_2 gas at a pressure of ~100atm for 5–7 days at room temperature [7]. They were then irradiated through a zero-order-nulled phase mask [8] having a period of 1.06μm with 193nm light [9] from an ArF excimer laser with an irradiance of ~160mJ/cm²/pulse and a pulse repetition rate of 50Hz for a duration of 5min. The laser cavities were formed by photo-imprinting two 5mm-long Bragg gratings near the ends of 4cm-long waveguides. The distance between the centre of the gratings was 3cm, which corresponds to a cavity free spectral range (FSR) of 3GHz. The gratings showed polarisation-dependent reflection bands centred around 1546nm. The centre Bragg resonance wavelengths for the TM polarised light were 0.3nm longer than the resonance wavelengths for light in TE mode. The polarisation dependence of the resonance wavelength of the reflectors is attributed to the stress-induced birefringence in silica-based waveguides on silicon substrates. Within the accuracy of the measurements, the maximum reflectivity (97%) and bandwidth (0.5nm) of the DBRs were identical for light in both the TE and TM modes.

The lasing characteristics of the waveguide lasers were measured using a Ti:Al_2O_3 laser as a pump source operating at a wavelength of 976nm. The waveguide lasers oscillated at a wavelength of 1546nm which corresponds to the Bragg resonance wavelength of the photo-induced reflectors. Fig. 2 shows the laser output of one laser as a function of the pump power. The threshold for laser oscillation occurs at an incident pump power of 60mW. The waveguide laser generates an output power of 340μW for a pump power of 300mW. The laser output starts to saturate for pump powers larger than 100mW. This saturation is due to pump bleaching caused from reduction in the population of the Er^{3+} in the $^4I_{15/2}$ ground state [1].

Temporal changes of the laser output were also measured using a photodetector and an oscilloscope. Strong relaxation oscillations

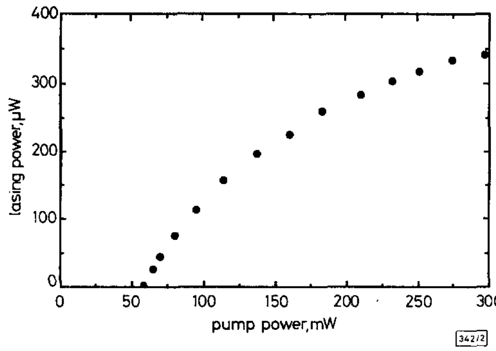

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Fig. 2 *Lasing power characteristic of Er^{3+}-P_2O_5-codoped silica waveguide laser with integrated 1546nm photo-imprinted Bragg reflectors*

Pump wavelength is 976nm

with frequencies between 100 and 200kHz were observed on top of the CW laser output. A similar phenomenon has been observed in Er^{3+}-doped fibre lasers [10]. The relaxation oscillations are attributed to a three level laser system which includes Er^{3+} clusters acting as saturable absorbers, with pump intensity fluctuations at the relaxation oscillation frequencies [11]. The relaxation oscillations can be suppressed using electrical feedback to control the pump intensity [10].

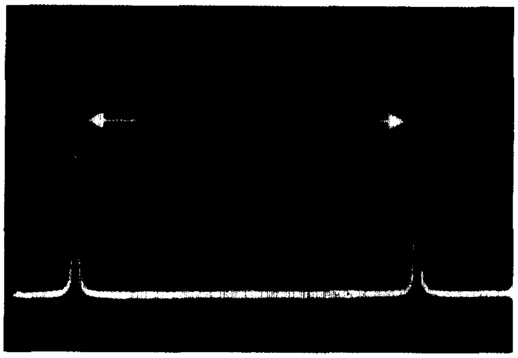

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Fig. 3 *Fabry-Perot spectrum analyser scan of laser output, showing single-frequency operation of waveguide laser*

Waveguide laser cavity FSR is 3GHz

The oscillation modes of the waveguide laser were examined using a scanning Fabry-Perot optical spectrum analyser with an FSR of 25GHz and a finesse of 100. Single frequency operation was obtained at pump powers less than 300mW. Fig. 3 is a photograph of a scan over one full FSR of the spectrum analyser confirming that the waveguide laser operates in a single longitudinal mode. This demonstration is the first, to our knowledge, of a single-frequency Er^{3+}-doped glass planar waveguide laser with integrated DBRs. The singlemode oscillation was robust and no mode hopping was observed with the application of mechanical shock.

We also measured the polarisation characteristic of the output light from two different waveguide lasers having the same cavity configuration and DBRs fabricated under similar exposure conditions. The output spectra of the lasers were measured using a Glan-Thomson prism and a grating-type optical spectrum analyser with a resolution of 0.1nm. Each laser emitted light in a different state of polarisation at pump powers less than 300mW. One waveguide laser oscillated in the TE polarised mode whereas the other oscillated in the TM polarised mode. The light from the TE polarised laser exhibited an extinction ratio of ~20dB at the lasing wavelength of 1546nm, while the amplified spontaneous emission had almost the same intensities in both the TE and TM modes, indicating that the gain of the waveguide had only a small dependence on polarisation. The light from the other laser had the same extinction ratio except it was TM polarised. The different polarisation state of the two lasers would confirm that the dependence of the gain and DBR reflectivity on polarisation are small, as mentioned before. Thus, slight differences in the overlap of the reflection spectra of the two DBRs between the polarisation modes, which were caused from slight differences in the exposure conditions, likely determine the polarisation state of the laser output.

In conclusion, single-frequency operation of planar waveguide lasers in the 1.5μm window were demonstrated. The lasers were equipped with DBRs integrated in Er^{3+}-P_2O_5-codoped silica waveguides on silicon substrates. The DBRs were photo-imprinted by irradiating the waveguides, which had been sensitised by H_2 loading, with ArF laser light at 193nm through a phase mask. The waveguide lasers generated linearly polarised 1546nm light having an output power of 340μW. Integration of wavelength-controlled lasers with passive waveguides may lead to new light sources for WDM optical communication systems.

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