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Single-frequency Er^{3+}-doped fibre lasers

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Single-frequency Er^{3+}-doped fibre lasers are emerging as interesting alternatives to distributed feedback (DFB) diode lasers for use in future high-capacity $1.5\mu m$ WDM communication systems, as well as in CATV, LIDAR, fibre-optic sensor and spectroscopy applications. In general, fibre lasers are fibre-compatible, scalable to high output powers and have low intensity noise and kHz linewidths.

Most work on single-frequency fibre lasers has been concentrated on: 1) long travelling-wave fibre ring-lasers [1]-[4], where single-mode operation is obtained by eliminating spatial holeburning (the factor which causes multi-mode operation in fibre lasers), and 2) short linear-cavity distributed Bragg reflector (DBR) fibre lasers employing fibre grating Bragg reflectors for feedback and mode suppression [5]-[11]. Recently also a fibre distributed feedback (DFB) laser, where the feedback is provided by one single fibre grating occupying the entire cavity length [12], and a single-frequency fibre Fabry-Perot micro laser [14] have been demonstrated.

Fibre ring-lasers

The main advantage of Er^{3+}-doped fibre ring-lasers is that they are (discretely) tunable over most of the Er^{3+} gain spectrum (>50nm) [4]. Tuning is effected by a broad-band PZT-tunable fibre Fabry-Perot (F-P) filter in combination with a similar narrow-band F-P filter for mode-selection inside the ring [3] or, alternatively, a combination of a broad-band tiltable interference filter and a fibre sub-resonator [4]. Quantum-noise- limited operation at higher frequencies has been demonstrated in such a laser [3]. Wavelength selectivity and tuning can also be achieved in a Sagnac-like fibre ring-laser with an external grating-reflector [2]. The linewidth of fibre ring-lasers can be narrower than 10kHz [1], [2] owing to the long cavity lengths. However, the long lengths give close longitudinal mode-spacing and make fibre ring-lasers susceptible to mode-hopping. Even with a combination of filters inside the ring, thermal drift of the cavity length will cause long-term mode-hopping. The latter can be eliminated by actively stabilising the laser through dithering of the cavity length (and hence the frequency of the laser) using a PZT fibre stretcher controlled by feedback from the output of the laser [4]. This and the need for intracavity filters, optical isolators and polarisation control make fibre ring lasers complex and expensive.

Fibre DBR lasers

Short Er^{3+}-doped fibre DBR lasers (see Fig. 1a and b) are much simpler than fibre ring lasers and can be made robustly single-mode. The laser wavelength is determined by the fibre-grating Bragg wavelength and can be set with an accuracy of ≤ 0.1nm, which is very difficult to achieve with DFB diode lasers. The fibre-grating Bragg frequency changes at about 1GHz/K and hence the frequency of DBR fibre lasers is relative temperature insensitive. Fibre DBR lasers can be tuned continuously by stretching or heating uniformly both the gratings and the intervening fibre [8]. The tuning range with PZT stretching is limited by the strength of the fibre and is typically <5nm, although tuning over 10-20nm might be possible in a high-strength fibre.

DBR fibre lasers are only robustly single-frequency provided that the grating bandwidth is kept below about 0.2nm and the laser length is reduced to a few cm to increase the axial mode spacing. The pump absorption in such short laser lengths is normally only a few percent and hence the slope efficiency of these lasers is very low (<1%), even when using the maximum Er^{3+}-concentration permitted by quenching considerations [7]. One solution to this problem is to use a MOPA (Master Oscillator Power Amplifier) configuration [9], where the residual pump power is used to pump a foowing fibre amplifier. However, the intensity noise of the source is increased by the use of the amplifier. This excess noise can be reduced (but not elimitated) by having an optical isolator between the laser and the amplifier. Note that short, heavily-doped Er^{3+}-doped fibre lasers are also susceptible to strong self-pulsation [7].

The above problems can be overcome by co-doping the Er^{3+}-doped fibre with Yb^{3+}, which increases the absorption at the pump wavelength by more than two orders of magnitude and enables highly-efficient operation of cm-long lasers [10]. We have recently demonstrated a 2cm long DBR Er^{3+}:Yb^{3+} co-doped fibre laser (as shown in Fig. 1a) with a stable single-frequency output power of 19mW at 1534nm when pumped by a 100mW 980nm diode laser (see Fig. 2). The relative intensity noise (RIN) of this laser was as low as -157dB/Hz above 10MHz, and the linewidth was about 300kHz [11]. Unfortunately, the alumino-phoshosilicate Er^{3+}:Yb^{3+}-doped fibre used in this experiment is not photosensitive and therefore the 2cm-long grating output coupler (with 70% reflectivity) had to be spliced to the doped fibre. However, by matching the spot sizes of the grating fibre and the Er^{3+}:Yb^{3+}-doped fibre the splice loss was <0.12dB, and the slope efficiency relative to the launched pump power was as high as 55%, close to the quantum limit of 64%. The other end-reflector of this laser was a dichroic mirror with 100% reflectivity at 1.5µm. A similar laser with the mirror replaced by a fibre grating with >99% reflectivity had a slope efficiency of about 46%. The slope effiency of a similar, lossless Er^{3+}-doped fibre laser is calculated to by 0.8% (see Fig. 2), which convincingly illustrates the advantage of including Yb^{3+}.

Fibre DFB lasers

Recently we have succeeded in writing fibre Bragg gratings with >99% reflectivity (refractive index modulation of about $2.1\ 10^{-4}$) directly in the same Er^{3+}:Yb^{3+}-doped fibre as was used in [11] by loading the fibre with hydrogen [12]. This has enabled us to demonstrated the first DFB (Distributed Feedback) fibre laser [13], with a single grating occupying the entire cavity length. Two different configurations have been demonstrated. The first is a uniform (ie non-phase-shifted) grating DFB laser with one 100% end-reflector (Fig. 1e). The slope efficiency of this laser relative to the incident pump power was about 5%, with a maximum output power of 2mW. In this case the spectrum normally had two modes symmetrically-spaced around the grating Bragg wavelength, as expected for a uniform DFB laser. The laser could be made single mode (with an optical linewidth of 60kHz) by slightly displacing the mirror, thus changing the phase relationship between the mirror and the grating. Using the same grating we have also demonstrated a phase-shifted fibre DFB laser with no end-reflector (Fig. 1d). The grating phase-shift was introduced by locally heating the centre of the grating. As expected, the optical spectrum of this laser was robustly single-mode with the wavelength equal to the Bragg wavelength and had a linewidth of about 300kHz. The output power from each end was about 2mW using an incident pump power of 127mW, giving a slope efficiency of about 5%. The relatively low slope efficiency is believed to be due to the small output coupling relative to the cavity losses and can be improved. Without the phase-shift (Fig. 1c) lasing did not occur owing to the higher threshold gain of a uniform grating DFB laser. Fibre DFB lasers should have all the advantages of fibre DBR lasers, with the additional advantage of better frequency settability and stability.

Fibre Fabry-Perot micro-lasers

Single-frequency operation can also be obtained in Fabry-Perot (F-P) fibre lasers using mirrors, provided that the cavity lengths can be made shorter than ~0.5mm. We have demonstrated a 100µm-long Er^{3+}:Yb^{3+}-doped fibre laser with a PZT-controllable air gap in the F-P cavity, providing continuous tuning over 4.5nm [14]. This is the shortest fibre laser ever reported. The output power saturated at about 20μW owing to the limited number of Er^{3+} ions causing a bottle-neck effect in the energy transfer from the Yb^{3+} to the Er^{3+} ions. A 500μm-long laser had a saturation output power of about 0.6mW. By splicing a 2.5m long Er^{3+}-doped fibre at the laser output, pumped by the residual pump power (ie. a MOPA), a maximum output power of 4mW was obtained. The laser was pumped by a 100mW 980nm diode laser.

In conclusion, there are a number of routes to single-frequency operation of Er^{3+}-doped fibre lasers, each of which has advantages. The choice of laser configuration will ultimately depend of the application, where tunability, linewidth, wavelength-settability or stability parameters may be important.

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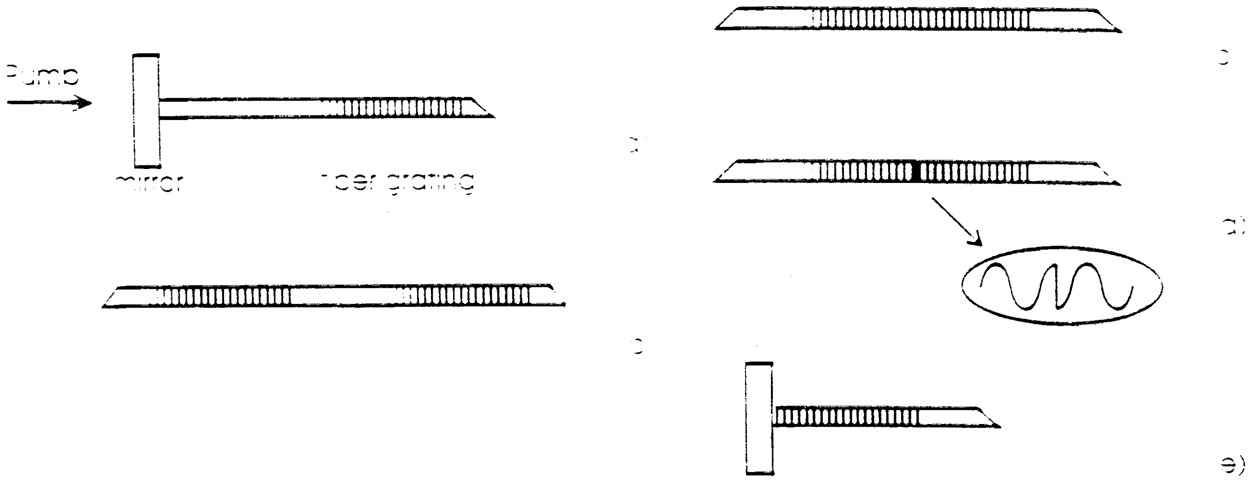

Fig. 1 Various fibre DBR (a and b) and DFB (c, d and e) laser configurations.

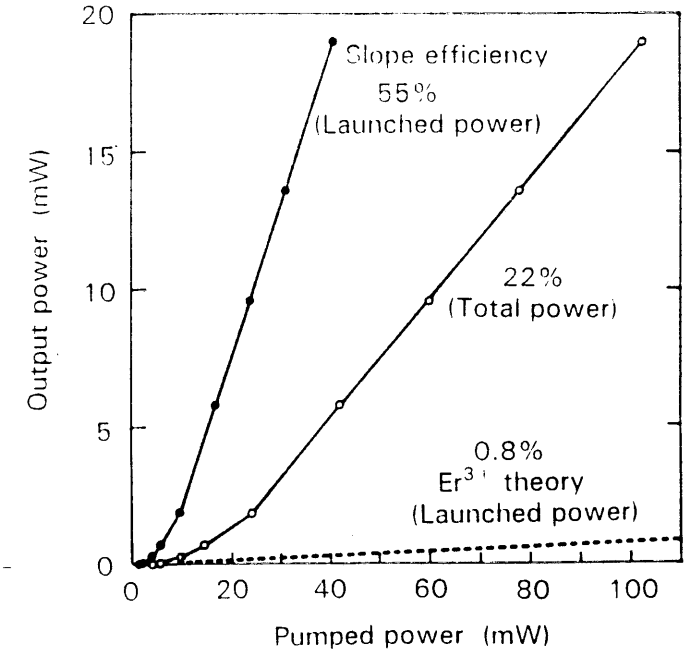

Fig. 2 Measured laser output power from a 2cm-long Er^{3+}:Yb^{3+}-doped fibre DBR laser as a function of total and launched diode pump-power. The calculated output power from an equivalent lossless 2cm-long fibre laser doped with Er^{3+} alone is shown for comparison.