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A mode-locked laser based on ytterbium doped holey fibre

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Abstract: We report the fabrication of a polarisation-maintaining, high-nonlinearity, anomalously dispersive, Yb^{3+} doped holey fibre and describe what we believe to be the first demonstration of a mode-locked holey fibre laser.

Introduction: Holey fibres (HFs) guide light by making use of a transverse structure of air holes running down the fibre length. The novel geometry leads to a strongly wavelength-dependent numerical aperture, which can result in a range of extraordinary optical properties including endlessly single mode guidance [1], very high optical nonlinearity [2] and tailorable dispersion properties [3,4]. Many of the unusual optical properties of HFs are of great interest for fibre laser applications. In particular, the availability of HFs with anomalous dispersion wavelengths extending down to the visible regions of the spectrum opens the exciting possibility of extending soliton laser techniques that have been developed for 1550nm operation of Er^{3+} lasers, to both Yb^{3+} doped, and Nd^{3+} doped fibre lasers. Moreover, the tight mode confinement possible within such HFs promises access to nonlinear effects at reduced power levels, and low laser thresholds. The fabrication of rare-earth doped HFs incorporating first Er^{3+} [5], and more recently Yb^{3+} has now been reported, and the first results on continuous-wave operation of Yb^{3+} holey fibre laser have been obtained [6]. In this letter, we demonstrate the fabrication of a polarisation-maintaining, high-nonlinearity, anomalously-dispersive Yb^{3+} doped HF, and report the first demonstration of a mode-locked holey fibre laser.

Fibre profile: An SEM image of the polarisation maintaining Yb^{3+} doped HF is shown inset in Fig.1. The fibre was produced using the conventional capillary stacking technique. The solid rod inserted within the stack to define the core was made from Yb^{3+} doped, alumino-silicate glass and which we estimate contained an Yb^{3+} concentration of 2000ppm. The fibre has an elliptical core measuring ~ 2.6x1.5μm. The core is supported on a network of fine glass struts of ~200nm width which isolates it optically from the rest of the fibre structure. The average hole-to-hole spacing and air-fill fraction of the fibre were ~2.7μm and ~70%, respectively. The elliptical core coupled with the high refractive index contrast between silica and air and small structure size result in an enormous form birefringence. Although high birefringence has previously been demonstrated in holey fibres [8], our measured beat length of 0.3mm at 1550nm is to our knowledge the shortest beat length ever reported for an optical fibre. The zero dispersion wavelength for this fibre is predicted to be substantially below 1μm using the method developed in Refs [4,9]. We have recently confirmed this experimentally in soliton experiments at 1030nm using this fiber and which will be reported elsewhere.

Laser results: Fig.1 shows our pulsed laser setup and which is based on a simple Fabry-Perot cavity, and that relies upon the principle of frequency shifted feedback as the mode locking mechanism. The cavity contained ~1m of HF in all of the experiments reported herein unless otherwise stated. The required frequency-shifting, spectral-filtering and polarisation selection within the cavity were provided by an acousto-optic tunable filter (AOTF) with a 3nm, 3dB bandwidth. The AOTF could be tuned over the entire gain bandwidth of Yb^{3+} transition by tuning the frequency of the RF drive by +/- 1 MHz, about the device's central operating frequency of 110MHz. In our particular cavity configuration the AOTF provided a ~220 MHz frequency downshift per cavity round-trip. The transmission efficiency of the device at the centre of the transmission passband was ~90% for light with the appropriate linear polarisation state. Note that we incorporated a $\lambda/2$ plate between the AOTF and the fibre to allow us to align the birefringence axes of the fibre relative to AOTF. This allowed us to achieve single polarisation operation of the laser. Coupling of the pump beam, and the signal beam into and out of the fibre was accomplished using an appropriate choice of aspheric, achromatic lenses. Laser output was extracted from the pump end of the cavity using a 980/1030 dichroic mirror that was angled at 20 degrees relative to the incident pump beam. Note that the required feedback from the pump end of the cavity was provided solely by the ~4% Fresnel reflection from the cleaved HF end. The laser was pumped using a fibre coupled, 966nm, single mode semiconductor laser capable of delivering up to 140mW of power at the HF launch input, we determined that ~25% of this pump radiation could be launched into the HF core.

In Fig.2 we plot the laser output power (at 1038nm) versus estimated launched pump power. The laser threshold is seen to be ~5mW which is reasonable given the cavity configuration, and the slope efficiency is estimated to be approximately 75%. This is an extremely respectable value for an Yb^{3+} doped alumino-silicate fibre and corresponds to ~ 80% quantum slope efficiency.

On examining the temporal characteristics of the laser output we found that stable, self-start mode-locking could be reliably obtained at average output powers in excess of 17mW. A photograph of the pulsed output is shown inset in Fig.2. This self-start threshold value is somewhat higher than we would have envisaged and results we believe from stray intracavity reflections, for example from the fibre cleave at the AOTF end of the cavity. At powers close to the self-start threshold fundamental mode-locking was obtained and a single pulse existed within the cavity. However, at higher operating powers multiple pulses were observed to form as is common for such lasers, particularly when operating in the anomalous dispersion regime. The spectral bandwidth of the pulses was ~0.1nm as shown inset in Fig.3. This corresponds to a pulse duration of ~15ps (assuming transform-limited Gaussian pulses). The high birefringence of our HF, although advantageous in terms of robustness of the system to environmental perturbations, prohibited us from achieving shorter pulses through nonlinear polarisation rotation effects in this instance [10]. However, this should be possible using more complex cavity arrangements [11].

The laser wavelength could be readily and rapidly tuned simply by changing the RF frequency applied to the AOTF. Mode-locked operation was obtained over a 20nm wavelength range from 1030nm to 1050nm as shown in Fig.3. Laser oscillation at longer wavelengths (up to 1.1μm) could be obtained using longer HF lengths of ~5m due to the absorption of short wavelength ASE, however it was difficult to achieve mode-locking in such long fibre lengths.

In summary, we have described the fabrication of a high efficiency, high nonlinearity, polarisation maintaining Yb^{3+} doped holey fibre and have provided the first demonstration of a mode-locked HF laser. We consider HFs have a lot to offer to the area of short pulse fibre lasers, and envisage the further demonstrations of a whole host of useful devices based on the use of such technology.

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Figure captions:

Fig.1 Schematic of the experimental setup for the laser cavity. DM:dichroic mirror, L1,L2:lenses, $\lambda/2$: half-wave plate, AOTF:acousto-optic tunable filter, and HR: highreflector. An SEM of the HF is shown inset.

Fig.2 Laser output power at 1038nm versus launched 966nm pump power . A typical oscilloscope picture of the pulse trains is shown inset.

Fig.3 Tuning curve of the laser output with a constant launch power of 35mW. Mode-locked operation is obtained at output powers in excess of 17mW. A typical mode-locked. pulse spectrum is shown inset

Figure 1

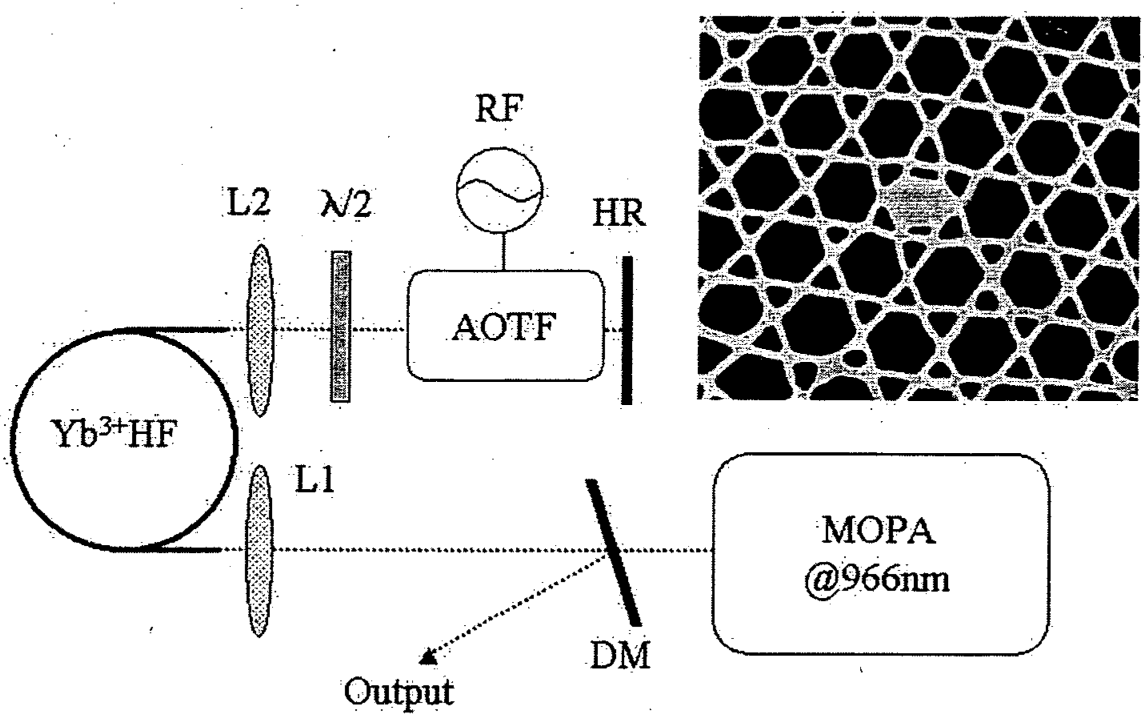
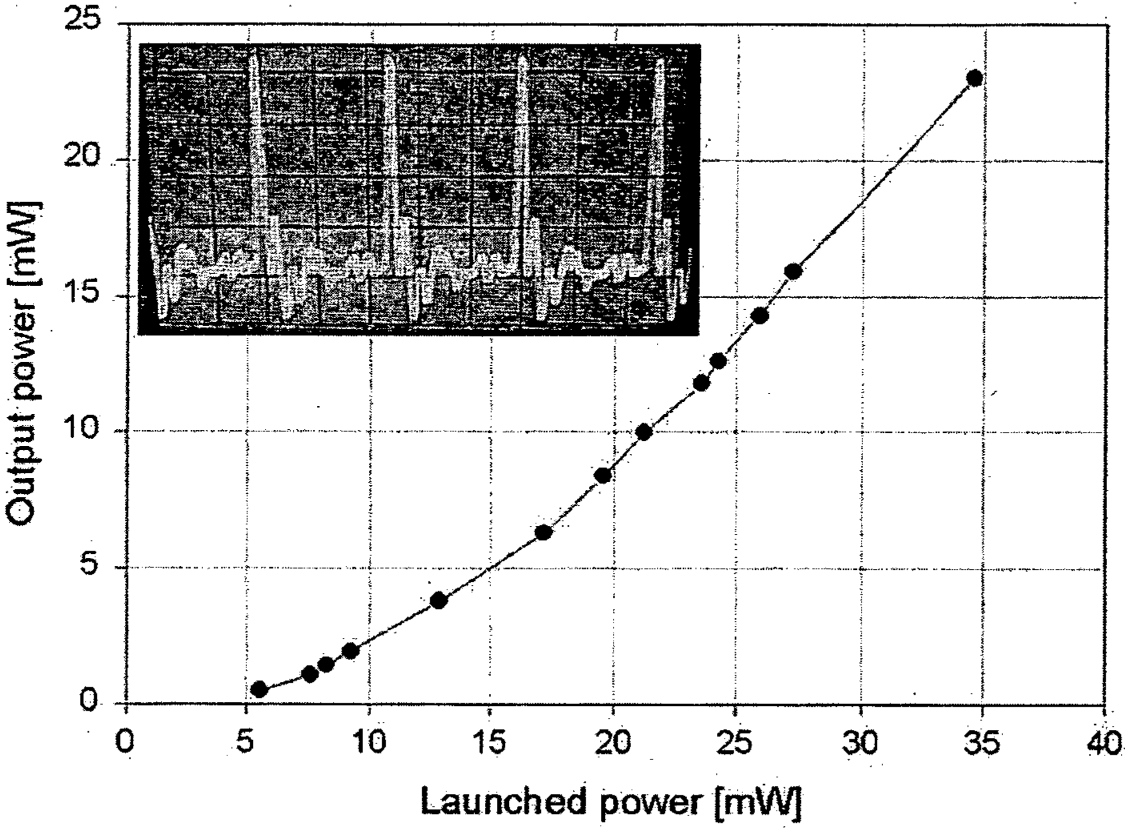
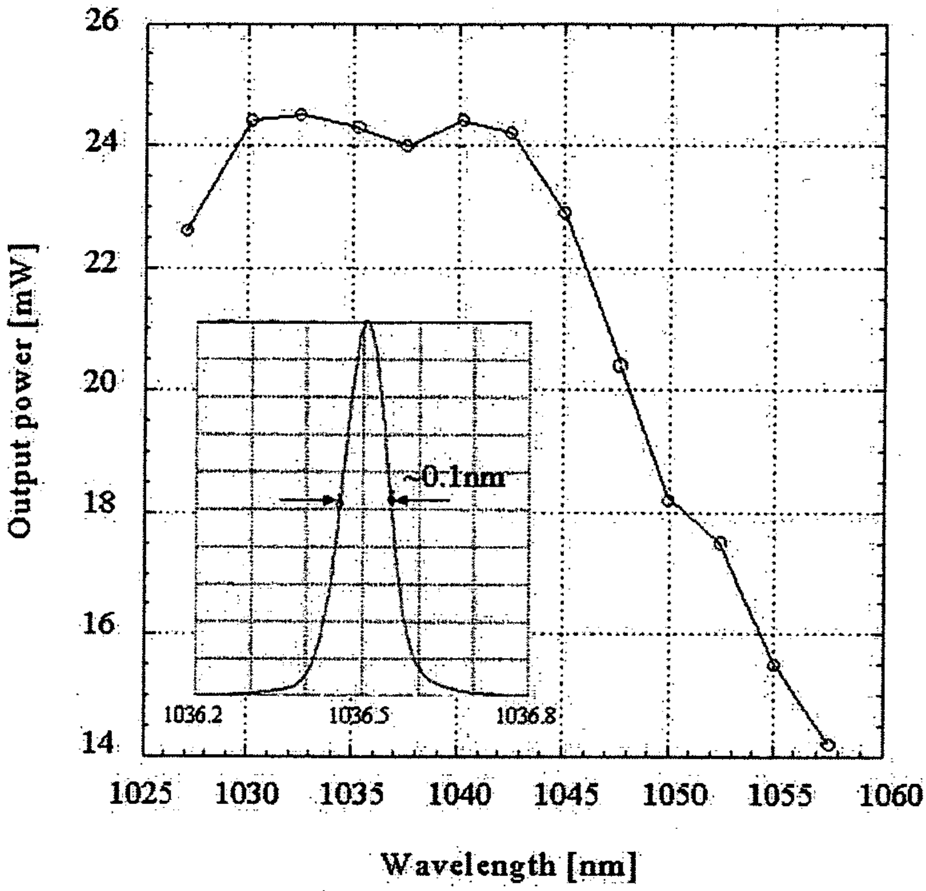


Figure 2



Output power [mW]
Launched power [mW]
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40

Figure 3



26
24
22
20
18
16
14
Output power [mW]
~0.1nm
1036.2
1036.5
1036.8
1025
1030
1035
1040
1045
1050
1055
1060
Wavelength [nm]