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A dual-operation Q-switched Erbium-doped fibre laser for distributed fibre sensing

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Abstract

A Q-switched Erbium-doped fibre laser has been developed and configured to provide narrowband and broadband operation using an all-fibre optical switch for distributed fibre sensing based on the Landau-Placzek ratio. Narrowband operation allows filtering of the Brillouin and Rayleigh signals and broadband operation minimizes coherent Rayleigh noise.

Introduction: In recent years, Brillouin scattering has received considerable interest for distributed temperature and strain sensing. The Landau-Placzek ratio method [1, 2] has recently been demonstrated in a distributed optical fibre temperature sensor (DOFTS), in which the Brillouin signal is referenced to the Rayleigh signal. A pulse of light is propagated down the sensing fibre and the backscattered Rayleigh and spontaneous Brillouin signals are interrogated. The Rayleigh signal is insensitive to temperature changes and is used to compensate for fibre attenuation and splice losses. The ratio between the Rayleigh and Brillouin signal intensity provides the Landau-Placzek ratio (LPR).

The LPR method requires the use of two sources having different bandwidths. A narrowband source is needed to allow optical filtering of the Rayleigh signal from the closely symmetrically spaced Stokes and anti-Stokes Brillouin components. However, the narrowband Rayleigh signal is noisy due to coherent Rayleigh noise (CRN) which would result in a LPR with degraded temperature resolution. The CRN is dependent on the temporal pulse width, the pulse linewidth and the detector bandwidth. Preliminary investigations indicate that a broadband source of not less than 2.5nm (~320GHz) is required to achieve a temperature resolution of 1 °C for a system offering a spatial resolution of 40m.

This paper describes a Q-switched Erbium-doped fibre laser source that can be rapidly switched from operating as either a narrowband source (~700MHz) or a broadband source (~375GHz) ideally suited to distributed sensing. This was achieved by using an all-fibre optical switch within the laser cavity to select either a narrow or broad bandwidth cavity end reflector.

Switch configuration and specifications: The switch used in the experimental laser configuration below was an all fibre acousto-optic device based on a four port null coupler [3]. The four port component is manufactured using standard single mode telecommunications fibre, and has the inherent advantages of low loss (<0.2dB), high conversion efficiencies (>99%), low drive power (<2mW) and is also suitable for broadband operation (>50nm). The null coupler is made from two fibres with diameters mismatched to the extent that the resultant coupler does not actually couple any light (see Fig. 1a). It is an example of an extreme wavelength flattened coupler. Like the wavelength flattened coupler, it can be made by pre-tapering one of two identical fibres along a short length before both fibres are fused and elongated together to form the coupler. This gives a device with identical single mode ports. Light in the other input fibre excites just the second mode in the waist. In both cases, the light propagates along the waist without further interactions and returns to the original fibre at the output end of the coupler.

A flexural acoustic wave propagating along the fibre (see Fig. 1b), causes a periodic refractive index perturbation in the waist. If a resonance condition is met - the acoustic wavelength matches the optical beat length between the modes - light can couple between the modes. Furthermore, if the amplitude of the acoustic wave is suitably adjusted, complete coupling is possible; light enters one fibre, excites just one mode in the waist, is acousto-optically coupled to the other mode, and emerges from the other fibre at the output.

Experiment and results:

Laser configuration: Fig.2 shows the configuration of the dual-operation, Q-switched Erbium-doped fibre laser. A 120mW, 980nm, fibre-pigtailed laser diode was used to pump the Erbium-doped fibre (0.18 N.A., 800ppm Er^{3+}concentration, unsaturated absorption of 45dB/m at 1550nm, second mode cut-off of 890nm, length of 100cm) via a 1550/980nm wavelength division multiplexer (WDM). The output light from the fibre end was focussed onto a plane mirror (99.9% reflecting at 1550nm), via an acousto-optic modulator (AOM) (100ns rise time, 80% diffraction efficiency), using a graded index lens. The AOM was operated in zero order mode.

A piezoelectric (PZT) disk (~0.2mm thick and 6mm in diameter), driven by an rf electrical supply to generate the acoustic waves, was connected to the coupler fibre of the switch by an aluminium horn (5mm diameter and 3mm high) which concentrates the acoustic wave at the apex. One end of a polarization controller (PC) was spliced on to the input port of the coupler to control the polarization state of the input light with the other end spliced on to the WDM.

A narrowband in-fibre grating (centre wavelength 1526nm, reflectivity 40% and linewidth 0.07nm) and a 19% reflectivity sagnac loop broadband mirror (95/5 coupler), were spliced on to the throughput and coupled ports of the switch respectively. The other ends of the output couplers were spliced on to a 90/10 coupler to obtain 90% and 10% of the signal power emerging from the diffraction grating and sagnac loop mirror output coupler respectively.

The rf was switched ON and the output signal emerging from the 90/10 coupler was monitored on an optical spectrum analyser. The signal intensity was maximized by adjusting the rf frequency and amplitude. The PC was found to have negligible effect, i.e. the switch was fairly insensitive to the polarization of the laser. A broadband spectrum was obtained. With the rf switched OFF, a narrowband spectrum was then obtained.

Fig. 3a shows the narrowband spectrum centred at approximately 1526nm obtained from the spectrum analyser. Since it was smaller than the smallest resolution (0.1nm) of the spectrum analyser, the bandwidth was measured using a scanning Fabry-Perot interferometer (FP). The FP was set up with a free spectral range (FSR) of 10GHz. Fig 3a, inset shows the spectra obtained with a bandwidth of 700MHz. Fig. 3b shows the broadband spectrum centred at approximately 1532nm with a 3dB bandwidth of approximately 375GHz (~3nm). Pulse widths for narrowband and broadband operation were approximately 180ns and 200ns respectively with corresponding powers of 2.5W and 1.5W. These were obtained at a repetition frequency of 1KHz.

Conclusion: A dual-operation Q-switched Erbium-doped fibre laser has been developed and configured for use in distributed sensing. A four port optical switch has been successfully used in the laser cavity to allow narrow and broadband operation. Switching may be achieved within 50μs. The two modes of operation allow a narrowband output (~700MHz) required for separation of the Rayleigh and Brillouin signals, as well as a broadband output (~375GHz) for generating backscattered Rayleigh signal with greatly reduced CRN. Periodic switching allows virtually simultaneous capturing of Brillouin and broadband Rayleigh signals for the first time, thus ensuring that the spontaneous Brillouin signal is correctly referenced even if fibre attenuation, splice or bend losses should vary during extended data collection cycles.

References

[1] WAIT, P.C., NEWSON, T.P.: 'Landau-Placzek ratio applied to distributed fibre sensing', *Optics Communications*, 1996, **122** (1) pp. 141-146.

[2] DE SOUZA, K., LEES, G.P., WAIT, P.C., NEWSON, T.P.: 'A diode-pumped Landau-Placzek based distributed temperature sensor utilising an all-fibre Mach-Zehnder interferometer', *Electronics letters*, 1996, **32** (23) pp. 2174-2175.

[3] CULVERHOUSE, D.O., FARWELL, S.G., BIRKS, T.A., RUSSEL P. St. J.: 'Four port fused taper acousto-optic devices using standard single mode telecommunications fibre', *Electronics letters*, 1995, **31** (15) pp. 1279-1280.

Figure Captions

Figure 1 a: Propagation of light through a passive null coupler.

b: Acousto-optic switching in the active coupler.

Figure 2 Configuration of the dual-operation Q-switched Erbium-doped fibre laser.

Figure 3 a: The narrowband spectrum with switch OFF, from the optical spectrum analyser.

inset: narrowband spectrum using a scanning Fabry-Perot interferometer.

b: The broadband spectrum with switch ON, from the optical spectrum analyser.

Figure 4 Plot of the temporal pulse widths of the narrowband and broadband pulses.

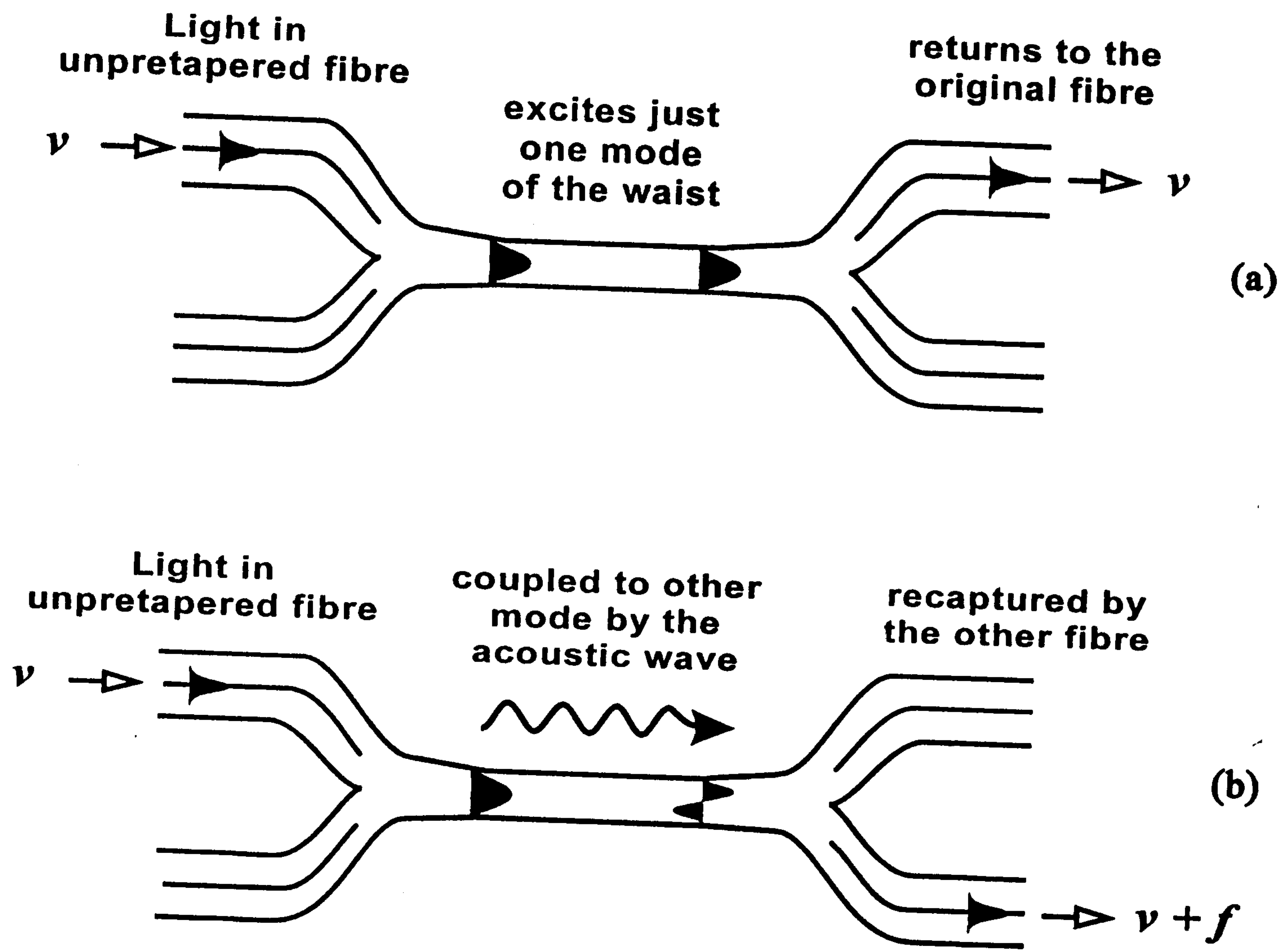

Light in
unpretapered fibre
ν
excites just
one mode
of the waist
returns to the
original fibre
ν
(a)
Light in
unpretapered fibre
ν
coupled to other
mode by the
acoustic wave
recaptured by
the other fibre
$\nu + f$
(b)

Fig. 1

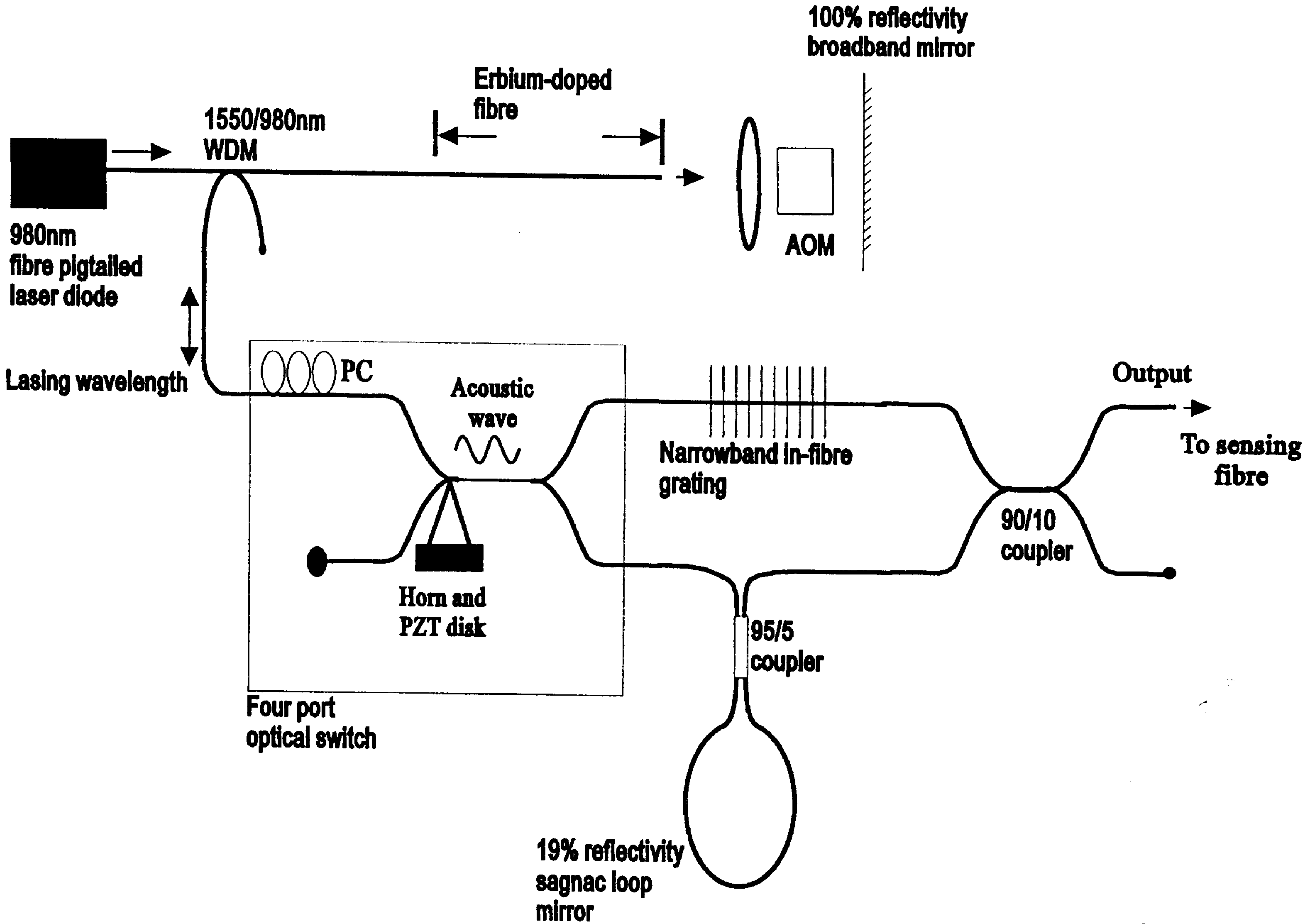
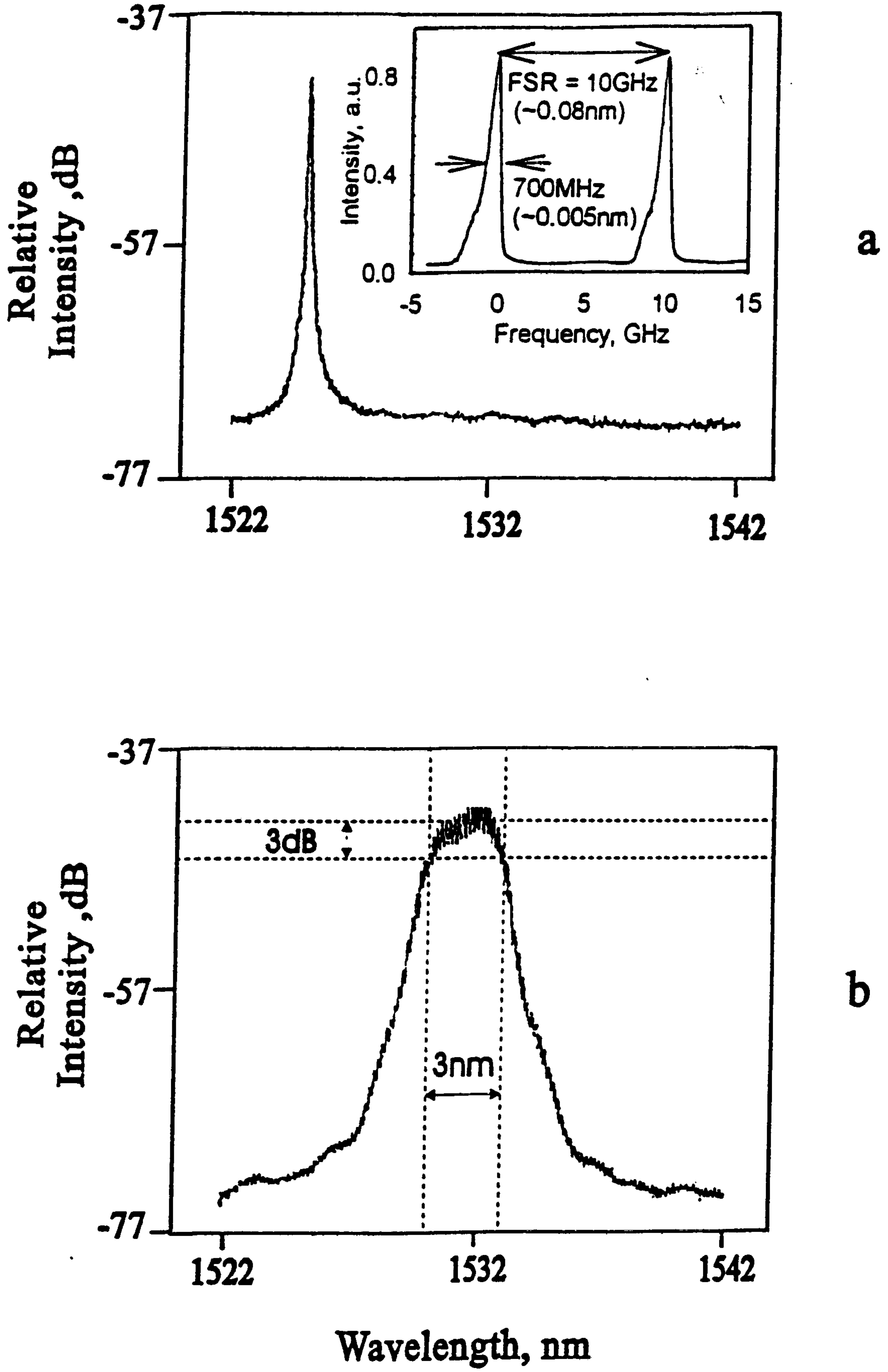

100% reflectivity broadband mirror
Erbium-doped fibre
1550/980nm WDM
980nm fibre pigtailed laser diode
AOM
Lasing wavelength
PC
Acoustic wave
Horn and PZT disk
Four port optical switch
Narrowband in-fibre grating
Output
To sensing fibre
90/10 coupler
95/5 coupler
19% reflectivity sagnac loop mirror

Fig. 2



-37
-57
-77
Relative Intensity ,dB
1522
1532
1542
Intensity, a.u.
0.0
0.4
0.8
FSR = 10GHz
(~0.08nm)
700MHz
(~0.005nm)
-5
0
5
10
15
Frequency, GHz
a
3dB
3nm
b
Wavelength, nm

Fig. 3