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Photon-injection polarisation-switching in fibre lasers

J.T.Lin, P.J.Wells, J.D.Minelly and D.N.Payne

Optical Fibre Group
Dept. of Electronics and Computer Science
Univ. of Southampton
Southampton SO9 5NH, U.K.
Telephone: (0703) 593584

Abstract

A novel photonic switching device based on polarisation switching by optical injection in fibre lasers is investigated. An all-optical switching device with an extremely low threshold (0.1μW) has been demonstrated. The mechanism of operation, experimental realisation and device characteristics are presented.

Introduction

All-optical modulation and switching are finding applications in optical information processing, fibre sensors and optical telecommunications. In this paper, we propose the novel concept of photon-injection polarisation-switching in fibre lasers, and report the first demonstration of such a switching device.

Mechanism of operation

Two orthogonal polarisation eigenmodes may be excited in the Fabry-Perot cavity of a fibre laser[1]. The polarisation orientations correspond to the birefringent axes of the active single-mode fibre which forms the cavity. At relatively low pump levels, only one polarisation mode oscillates, and polarisation mode competition causes lasing action in this polarised component to deplete the majority of the population inversion. However, the fibre laser, owing to its single-mode waveguide structure and long length, provides an ideal environment for the build-up of superfluorescence necessary for lasing action. Thus for the single polarisation operation, the lasing polarisation mode has the usual linear lasing characteristic, whilst the other polarisation component remains as superfluorescence with an exponential input/output relationship. As a result of the fact that two competing polarisation eigenmodes share the same gain medium, the operating polarisation mode can be switched to its orthogonal counterpart if a sufficient number of coherent photons having the correct polarisation are injected into the cavity.

A theoretical analysis shows that the threshold power of the injected photons at lasing wavelength P_o needed for switching to occur is given by

$$P_o \geq (P^x - P^y)\ \eta\ \xi\ \frac{\nu_o}{\nu_p} \qquad (1)$$

where η is the pumping efficiency factor[2], and ν_o and ν_p are the lasing and pump frequencies, respectively. The parameters P^x and P^y are the effective absorbed pump power for the x and y modes, respectively, and depend on the polarisation anisotropy of the stimulated emission cross-section of the active ions in the glass matrix as well as on the polarisation orientation of the linearly-polarised pump source[3]. The parameter ξ is the solid angle ratio and can be expressed as

$$\xi = 1 - \frac{n_{cl}}{n_{co}} \qquad (2)$$

where n_{cl} and n_{co} are refractive index of the cladding and core, respectively. Physically, ξ is the fraction of the spontaneous emission which is captured by the fibre. An extremely low threshold is expected from eq.(1).

Experimental realisation

In order to demonstrate feasibility, we have fabricated the new switching device with a Nd^{3+}-doped fibre laser pumped by a laser diode. Either CW or pulsed coherent photons at the lasing wavelength were injected into the cavity of the fibre laser via an intracavity coupler. Low-threshold polarization switching was observed in both cases.

A schematic of the experimental set-up is shown in Fig.1. The laser cavity was formed from a 2m-long active fibre spliced to an intracavity coupler made of undoped fibre. The dopant concentration of the active fibre was 300ppm. Both the active and passive fibres had the same NA (0.21) and the same cutoff wavelength (850nm). The active part of the cavity was made into a 3cm diameter coil in order to define the fixed axes of the cavity eigenmodes. A fibre polarisation controller working as a $\lambda/2$ plate was applied to ensure the coincidence of the birefringent axes between the active fibre and the intracavity coupler. The coupler had a coupling efficiency of 15% at the lasing wavelength of $1.08\mu m$. A laser diode operating at 813nm was used as the pump source. The output mirror of the cavity, M_2, had 80% reflectivity at the lasing wavelength. A polarisation beam splitter, having an extinction ratio of 30dB, was located in the optical path of the laser output to allow the two orthogonal polarisation components to be detected separately. The threshold power for the laser was then measured to be 4mW. For an absorbed pump power of 4.8mW the laser was operated in its single-polarisation state with an output power of $120\mu W$. A 15.4dB polarisation extinction ratio was measured from port 4 (see Fig.1) indicating that the coupler adequately preserved the polarisation states.

A single-polarisation fibre laser was used to provide the CW injection light. This light is linearly polarised with exactly the same wavelength as the operating laser, since the active fibres and pumping sources are identical. Alternatively, a tunable, pulsed dye-laser was used in the experiments, giving 6ns pulses with a 30Hz repetition rate. The polarisation of both the CW and the pulsed injected light was controlled by a $\lambda/2$ plate.

It was observed that when a pulse of light was injected with the same polarisation as the operating mode, the laser operated as an oscillator/amplifier and gave a train of pulses spaced at the resonator round-trip time, as seen from Fig.2. The pulse train length was measured to be $1\mu s$. However, when light of orthogonal polarisation was injected into the cavity, the pulse was amplified while it extracted the population inversion until it finally extinguished the initial lasing polarised mode (Fig.3). After the effects of the injected light pulse have disappeared, the operating lasing mode builds up oscillation again, as shown in Fig.3.

It was also observed that CW light can switch the operating mode from one polarisation to its orthogonal counterpart. This can be clearly seen from the Fig.4, where the upper trace is for the preliminary x-polarised mode, whilst the lower is the y-polarised mode. Here the injected light was chopped by a mechanical chopper.

Device characteristics

As expected from the theoretical analysis, the switching threshold for such a device is extremely low. Only 0.1μW of photon power is sufficient for CW switching of the laser.

The on/off ratio of switching is also high, since the lasing action can be totally extinguished, leaving only the fluorescence level, as seen in Fig.4. A ratio of 12:1 has been measured for CW switching, even when the fluorescence was detected over its full spectral bandwidth.

A switching time of 4μs was measured, and is limited by the photon lifetime in the cavity. A lower reflectivity of the output mirror will therefore give faster switching at the expense of a higher pump level and switching threshold.

It was also found that the switching effect can tolerate a relatively large wavelength variation. No significant effect was observed when using pulsed, injected light with a tuning range of 10nm.

Conclusions

A photon-injection polarisation-switching device has been demonstrated with a LD-pumped Nd^{3+}-doped fibre laser. Such an all-optical switching device offers the advantages of extremely low threshold, a high switching extinction ratio and simplicity of device configuration. The switching time is limited by the photon lifetime in the laser cavity but could be reduced to sub μs levels.

Although for convenience feasibility has been demonstrated using a Nd^{3+}-doped fibre laser, operation at a wavelength of 1.55μm using a Er^{3+}-doped fibre laser is possible.

Photon injection into the laser cavity allows not only polarisation switching but also the active control of the laser performance. Operations such as mode-locking and spectral narrowing of the fibre lasers can be envisaged. The potential applications of the device also include optical logic, optical sensing and optical signal processing.

References

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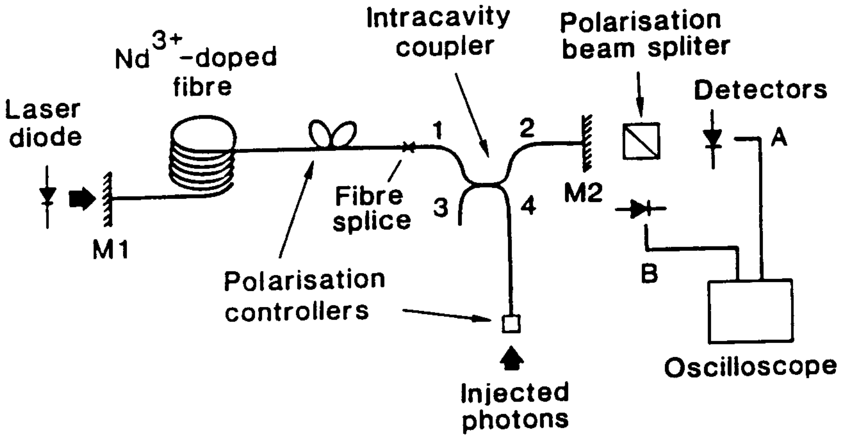

Fig.1 Experimental set-up.

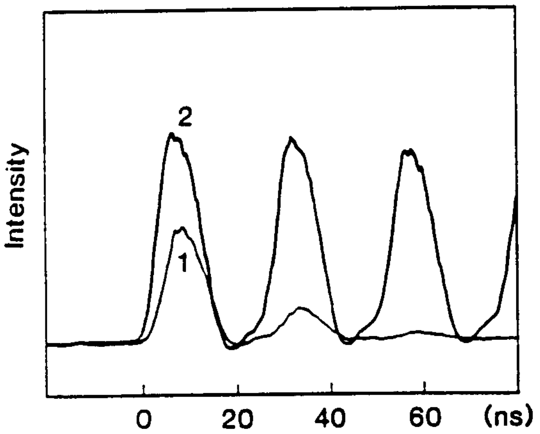

Fig.2 Pulse train showing amplification of a single injected pulse by a pumped Fabry-Perot cavity. The injected pulse has the same polarisation as the lasing mode.
Trace 1: Pulse train when cavity is unpumped.
Trace 2: Pulse train when cavity is pumped.

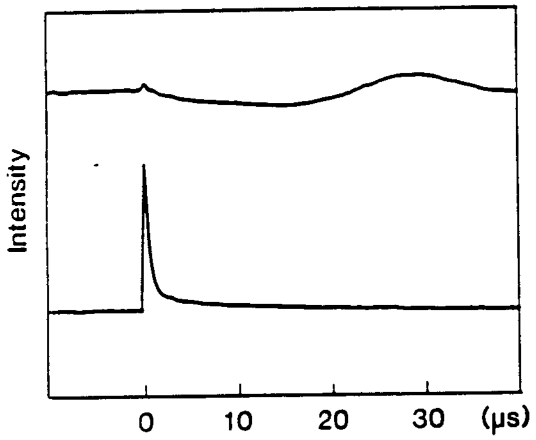

Fig.3 Curves showing the lasing x-polarisation mode being extinguished by the amplification of the injected y-polarisation pulse.
Upper trace: x-polarisation mode.
Lower trace: envelope of pulse train of the y-polarisation mode.

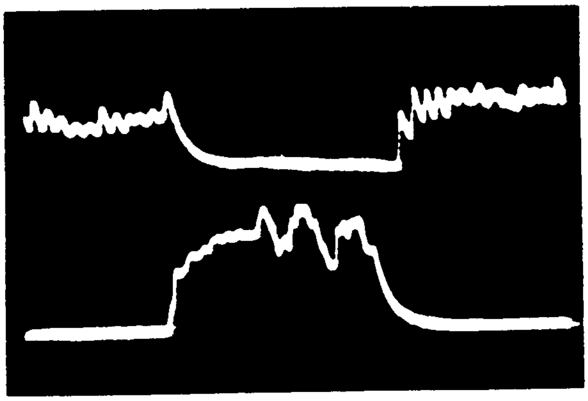

Fig.4 CW polarisation switching in a fibre laser.
Upper trace: Intensity of x-polarisation mode detected by D_1.
Lower trace: Intensity of y-polarisation mode detected by D_2.