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# Actively mode-locked and passively Q-switched operation of a thulium-doped fibre laser using a multi-quantum-well asymmetric Fabry-Perot modulator

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**Abstract**

An actively mode-locked and passively Q-switched thulium-doped fluorozirconate fibre laser using an AlGaAs/GaAs multi-quantum-well (MQW) asymmetric Fabry-Perot modulator (AFPM) is reported. This is the first demonstration of active mode-locking of fibre lasers using MQW modulators. Mode locked pulse trains of 6ns pulsewidth are obtained within a Q-switched envelope of 400ns duration.

## Introduction

Rare-earth-doped single-mode optical fibres [1,2] are ideal for use in mode-locked laser sources as their large fluorescence linewidths give the potential for ultra-short pulses. However, to produce ultra-short pulses from such devices, very fast modulators or saturable absorbers are necessary. Recently there has been rapid development of active and passive multi-quantum-well (MQW) devices for high speed modulation [3]. Several workers have demonstrated mode-locked lasers using MQW structures as fast saturable absorbers [4,5]. In addition, high-speed optical intensity modulators termed AFPMs (asymmetric Fabry-Perot modulators) which utilise the quantum-confined Stark effect have been developed [6].

We report for the first time an actively mode-locked and passively Q-switched thulium-doped fluorozirconate fibre laser operating in the 810 nm wavelength region, using an AFPM both as an amplitude modulator and as a saturable absorber.

## Experimental

Figure 1 shows the experimental set-up. Optical gain was provided by a 188.5cm length of thulium-doped fluorozirconate fibre [2] containing 1000ppm by weight of $Tm^{3+}$. The core diameter of the fibre was $3.5\mu m$, which ensured single-mode operation at both the pump and lasing wavelengths. Optical pumping was provided by a Ti-sapphire laser operating at 785nm via a dichroic mirror butted against one fibre end. The dichroic mirror had high transmission (75%) at the pump wavelength and high reflection (99%) at the lasing wavelength (810-815nm). At the other end of the fibre the output was collimated and focused onto the AFPM which acted as the other mirror. 4 times magnification of the fibre spot size was achieved by using respectively x40 and x10 microscope objectives. The AFPM employs 54 periods of 110Å AlGaAs/42Å GaAs MQW having a zero bias e1-hh1 exciton peak at 806nm. The epitaxial structure was deposited using atmospheric pressure

MOVPE and the conventional reagents of arsine, trimethylgallium and trimethylaluminium. Silane and dimethylzinc provided n and p doping of the Bragg stack and the $Al_{0.3}Ga_{0.7}As$ respectively, in this PIN configuration. Detailed discussion of the operation of AFPMs can be found elsewhere [6]. The AFPM used in this experiment had a high reflection modulation depth (50% at 810nm for a 0-10V bias voltage change), an active area of 200$\mu$m x 200$\mu$m and a modulation bandwidth of 400MHz. It was driven by a DC voltage source and an RF signal generator connected via a bias-T. Output coupling from the laser was provided by a pellicle beamsplitter with a reflection coefficient of 6.6%. An 810nm bandpass filter with 18nm FWHM prevented residual pump from impinging on the AFPM. The output beam was detected using a high-speed InGaAs detector.

First, the characteristics of the laser were examined without driving the AFPM. By changing the focusing conditions on the modulator, three lasing regimes were obtained, namely, CW operation, continuous spiking and passive Q-switching. The maximum CW optical intensity on the modulator was approximately 12kW/cm$^2$, significantly larger than the zero bias saturation intensity we have measured for similar devices of 3kW/cm$^2$. In the CW regime an incident pump threshold of 72mW was obtained. It was not possible to cut-back the fibre to determine the absorbed pump power directly, but assuming a typical absorbed fraction of 33% of the incident pump, the slope efficiency was 4.5%. A CW output power of 1.4mW was obtained for an incident pump power of 167mW.

The CW operating regime occurred when the average photocurrent from the MQW device was at a maximum and corresponded to maximum average saturation of the MQW. In this condition no optical modulation could be obtained from the AFPM. The continuous spiking and passive Q-switching regimes however were due to incomplete saturation of the device causing a nonlinear reflection coefficient from the MQW structure. In the case of continuous spiking, pulse trains of 2$\mu$s pulsewidth with 40$\mu$s period were obtained. The peak power was approximately 4 times the CW output power level. Continuous spiking ceased in favour of passive Q-switching when the focused spot size on the AFPM was slightly changed so changing the non-linearity. Figure 2 shows the Q-switched pulse with a width of 200ns, which is equivalent to that obtained with a mechanical (chopper) Q-switch. In this regime, the repetition rate was more unstable than for continuous spiking and the period between pulses was 200-300$\mu$s. The peak output power was 0.43W when the incident pump was 167mW. Mode beating corresponding to the round-trip cavity frequency of 48.36MHz was also observed. The above data were taken under zero-bias conditions. However, it should be noted that the occurrence of each of these 3 regimes was strongly affected by the bias voltage as well as the focusing conditions on the AFPM. In particular, the CW regime could be converted to the spiking regime by applying a reverse bias voltage. This is because the applied bias voltage acts to sweep out optically generated carriers and hence increases the saturation intensity.

Mode-locked operation was obtained when a 48.36MHz sinusoidal wave was applied together with suitable DC bias to ensure the AFPM was not forward biased. Mode-locked operation was only obtained, in this configuration, when the laser operated in the Q-switched regime. This was because the small signal present in the Q-switched pulse leading edge was insufficient to saturate the modulator and hence modulation at the round-trip frequency could be applied. It should be noted however that the shortest mode-locked pulsewidths did not correspond with the shortest Q-switched pulsewidths. Clearly, saturation of the AFPM was critical in determining the mode-locked characteristics. Figure 3 shows the mode-locked pulse train obtained under a 400ns Q-switched envelope when 0 to -10V sinusoidal modulation was applied. A pulse duration of 6ns and maximum peak power of 0.54W were obtained. Reducing the modulation amplitude or detuning the modulation frequency degraded the pulse train into mode beating, indicating that active mode-locking was taking place.

## Summary

Using an AFPM, we have demonstrated mode-locked operation in a Q-switched regime for a Tm-doped fibre laser operating at 810nm. The passive Q-switching and spiking behaviour noted in the absence of modulation is caused by saturation of the absorption in the MQW, which leads to non-linearity in the reflection coefficient. Sensitivity to both focused spot size on the modulator and saturation intensity via the bias voltage was both expected and observed. Optimisation of the power density on the modulator is likely to overcome the saturation effects and enable active mode-locking in the CW regime. This should result in substantially-narrower mode-locked pulsewidths since it will overcome the reduction of modulation depth under saturation. One possibility to optimise the power density is to use a coupled-cavity arrangement to minimise the power incident on the AFPM. In addition, MQW structures with greater saturation thresholds can be fabricated. We believe the technique will also be readily extendable to other wavelengths. In particular, InP/InGaAs MQW modulators will be of great interest for mode-locking of Er-doped fibre lasers operating around 1.55$\mu$m.

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## Figure Captions

1. Experimental setup of mode-locked Q-switched Thulium-doped fibre laser.

2. Passively Q-switched pulse.

3. Mode-locked pulse within a Q-switched envelope.

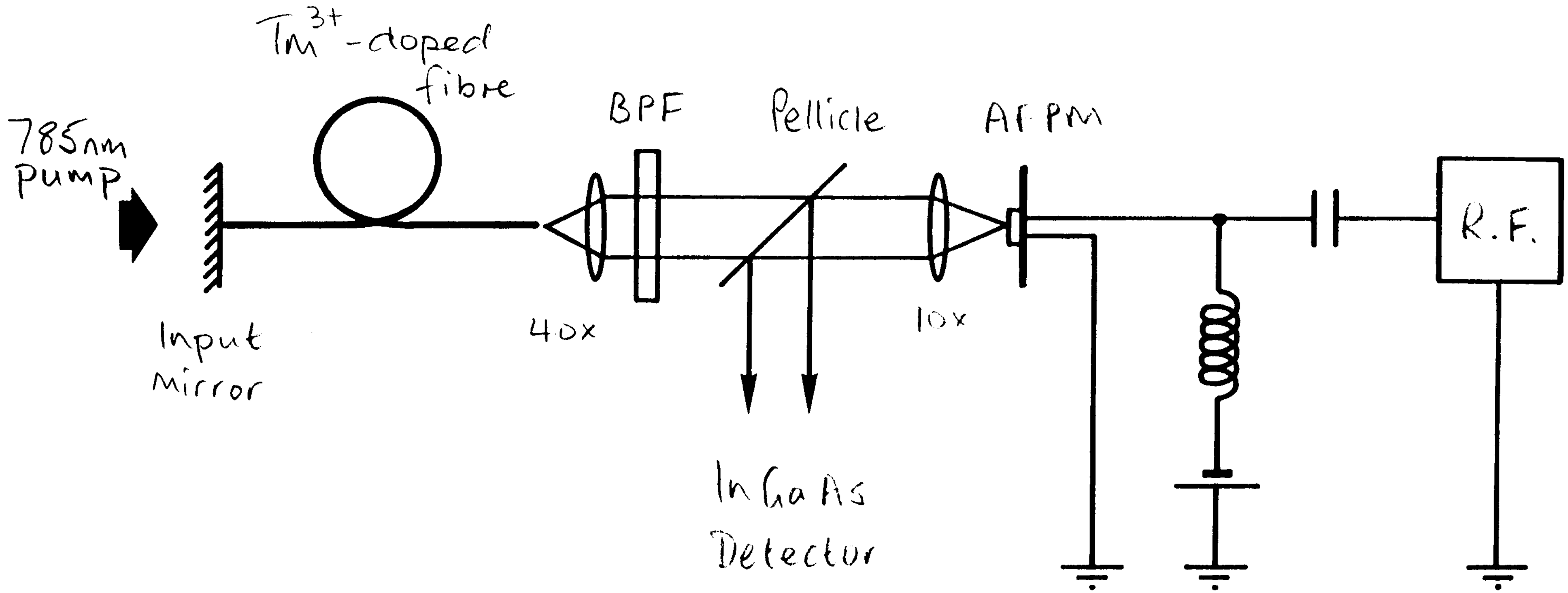
785nm
PUMP
Input
Mirror
Tm3+-doped
fibre
40x
BPF
Pellicle
InGaAs
Detector
10x
Af PM
R.F.

Fig 1

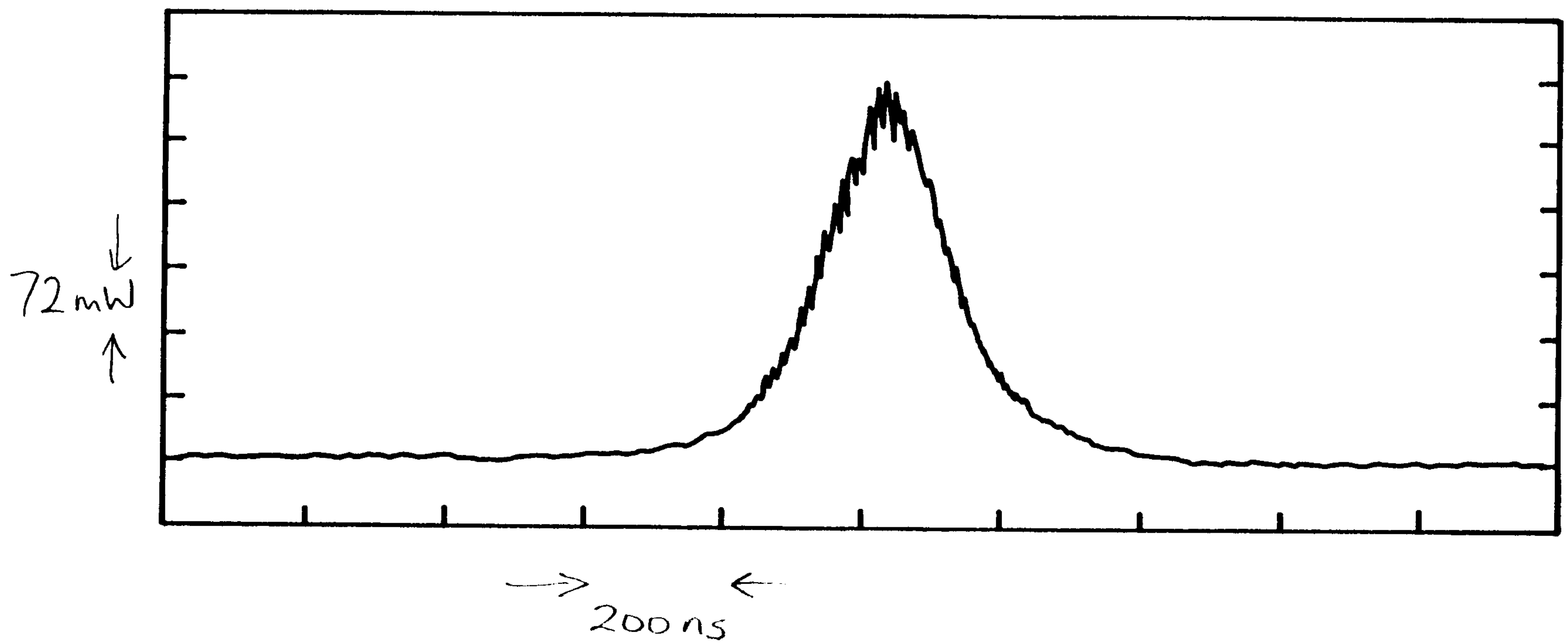


Fig 2.

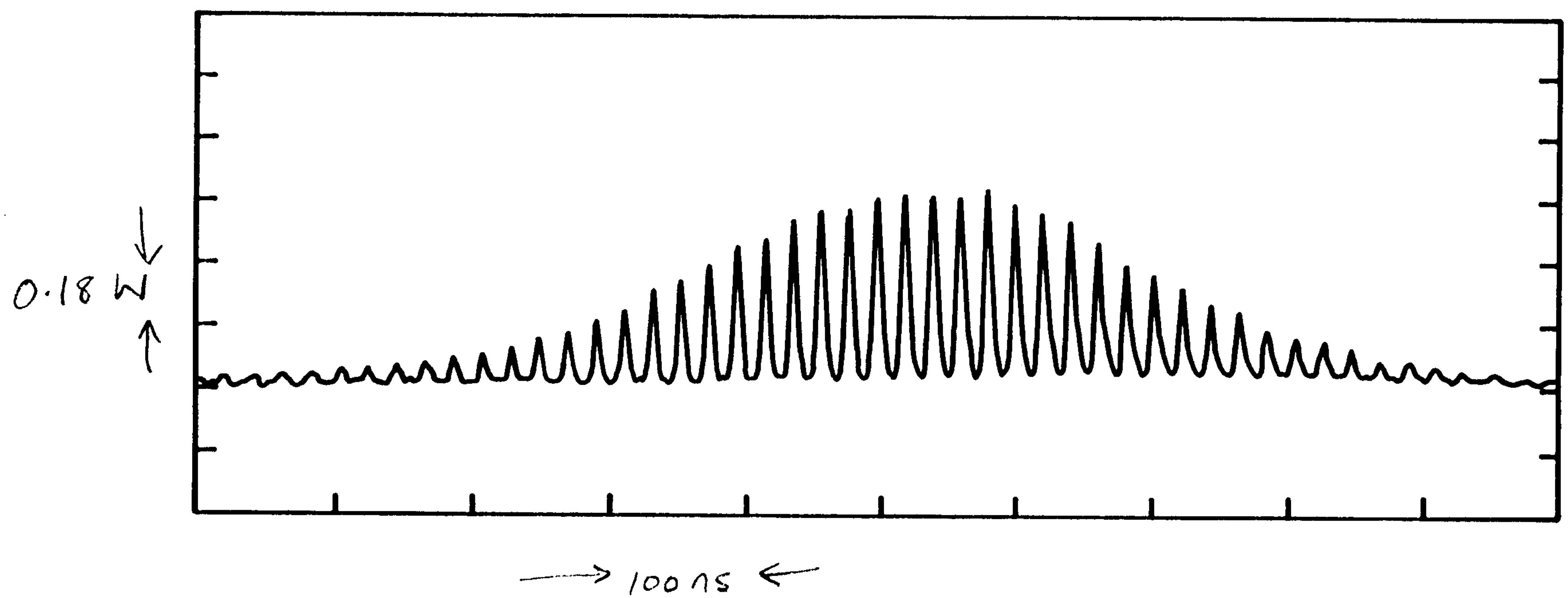


fig 3