120 V of gate voltage and 700–800 V of anode voltage are required instead of 90 and 600 V, respectively, according to our previous data [6]. However, these magnitudes of voltages (V_g = 120 V, V_a = 700–800 V) are sufficient to lead to cathode tip sputtering, even though the situation is dependent upon the quality of the cathode and anode plate itself. Consequently, with the MCP, we achieve a high enough current density of electrons to give sufficient brightness of phosphor, originally generated under a weak electric field.

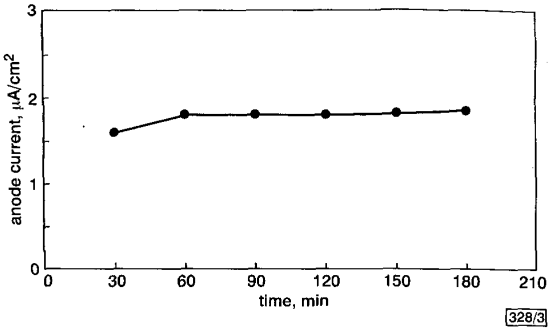

Fig. 3 *Emission current stability of FED in operation with MCP for 180 min*

V_a = 600 V, V_{TOP} = 800 V, V_{BOT} = 200 V and V_g = 90 V

Conclusion: A specially fabricated MCP has been successfully applied to the FED to obtain a bright moving picture, where the FED is operated by line-by-line addressing in the driving circuit. The results show that the anode brightness is about three times higher with an MCP, and the MCP itself also has a function of electron focusing. In addition, the current stability of this MCP was maintained for 180 min without fluctuation.

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Demonstration of passive modelocking through dissipative four-wave mixing in fibre laser

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Experimental observation of passive modelocking by dissipative four-wave mixing in an erbium-doped fibre laser containing a dual-peak fibre Bragg-grating filter is reported. The laser operates in the normal dispersion regime and generates optical dark pulse trains with a repetition rate of 80 GHz.

Introduction: The generation of stable optical pulse trains with ultra-high repetition rates in erbium-doped fibre lasers is an important issue for future high-bit-rate telecommunication systems. Several methods that overcome the limits of electronic modulators have recently been investigated. Attempts have been made to improve active modelocking techniques, which have been used successfully in the past for repetition rates in the range 1–40 GHz. High-order active modelocking schemes [1] and time-division multiplexing of lower bit-rate actively-modelocked lasers [2] appear the most promising of these solutions, and have both led to lasers exhibiting repetition rates exceeding 150 GHz. On the other hand, passive modelocking techniques that take advantage of the fibre nonlinearity to create an effective ultra-fast saturable absorber appear as simpler solutions to generate all-optical ultra-high repetition rate pulse trains. In the past, however, passive modelocking has mostly been studied with lasers operating in the soliton regime, which results in excellent individual pulse characteristics but also leads to pulse repetition rate instabilities. Pulses as short as 77 fs have been generated in stretched-pulse fibre lasers [3], but the maximum repetition rate of these lasers has been limited to a mere 1 GHz [4]. In response to this limitation, modulational instability has been proposed as a modelocking mechanism, yielding repetition rates in excess of 100 GHz [5, 6]. Modulational instability being at the origin of the pulse formation process, ultra-high repetition rates can be generated naturally, with a potential to reach the 1 THz barrier, far beyond the limit of active modelocking schemes. Another related technique, called dissipative four-wave-mixing modelocking (DFWM), has also been recently proposed theoretically [7]. This technique is particularly attractive because modelocking can be achieved either with an overall anomalous or normal cavity dispersion, leading to the generation of bright or dark pulse trains, respectively. To the best of our knowledge, however, this technique has never been the object of an experimental study. The aim of this Letter is to show how promising and efficient DFWM modelocking is by demonstrating the generation of 80 GHz dark pulse trains directly from an erbium-doped fibre laser with an overall normal dispersion.

DFWM modelocking is based on the presence of a dual-peak bandpass filter in the laser cavity [7]. The modelocking mechanism has been identified as being a process in which only two modes experience net positive gain and transmit their energy by four-wave-mixing to their higher-order harmonics, which undergo net negative gain owing to the bandpass nature of the filter. As a result of the parametric wave mixing, the phases of the generated longitudinal modes are locked and chirp-free pulses are formed [7]. The repetition rate of the laser is controlled by choosing the frequency separation between the two peaks of the filter. Theory reveals that no phase matching is required for the modelocking to be effective, because of the presence of gain dispersion. Tuning the relative amount of chromatic and gain dispersion and intracavity power also allows us to control the mark-to-space ratio of the generated pulse train.

Experiment: Our experiment was performed with the ring laser cavity configuration shown in Fig. 1. The dual-peak bandpass filter that is the key ingredient for DFWM modelocking has been implemented with a non-chirped fibre Bragg grating (FBG) filter connected to the ring cavity through a single-polarisation optical circulator. The reflectivity spectrum of the FBG filter is shown in Fig. 2. It shows Bragg resonance at 1547.5 nm (main peak), and periodic resonances caused by the nonuniform DC refractive index on the short wavelength side. The strongest of these resonances is considered as the second peak of our filter (1546.6 nm), as required by theory [7]. As can be seen in Fig. 2, there is a relatively small difference between the reflectivity of the two main peaks of the FBG filter. This has not prevented us from observing DFWM modelocking, as this imbalance can be compensated for by adjusting the settings of the polarisation controllers (PCs) that are incorporated into the laser cavity. By finely tuning the PCs, we can adjust the cavity loss and achieve balance between the wavelengths, thanks to polarisation-dependent losses of components such as the circulator and the isolator. Besides the FBG filter and the PCs, the cavity contains a 25 m long erbium-doped fibre amplifier pumped by a set of four DFB lasers emitting a total power of 410 mW at 980 nm, a 200 m long dispersion compensating fibre (DCF), two polarisation-maintaining (PM) isolators, and a 10/90 PM output coupler. The FBG filter sets the operating wavelength of the laser, $\lambda \sim 1547$ nm, for which our DCF exhibits normal dispersion, $D = -19.2$ ps/(nm·km), which makes our laser operate in the dark pulse regime [7].

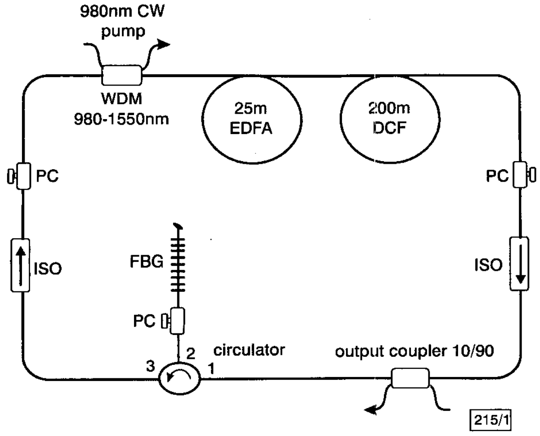

Fig. 1 *Experimental setup*

WDM: wavelength-division multiplexer; EDFA: erbium-doped fibre amplifier; PC: polarisation controller; DCF: dispersion-compensating fibre; ISO: isolator; FBG: fibre Bragg-grating

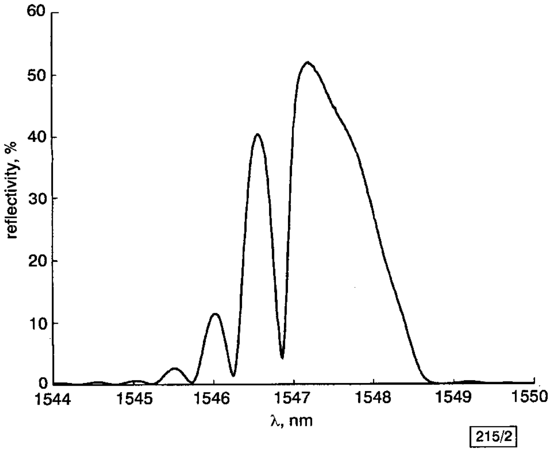

Fig. 2 *Reflectivity spectrum of FBG filter*

When the polarisation controllers are adjusted for optimum operation, the laser produces harmonic sidebands by four-wave mixing, and a continuous-wave pulse train is observed. Figs. 3*a* and *b* show the optical spectrum and the corresponding autocorrelation trace of the laser output for an intracavity power of 62 mW. We can see in Fig. 3*a* that the spectrum is remarkably symmetric despite the asymmetry of our filter. The autocorrelation trace confirms the generation of a pulse train with an 80 GHz repetition rate, which corresponds to the frequency separation between the two main peaks of the dual-peak filter. The 53% intensity background present on the autocorrelation trace of Fig. 3*b* occurs because we are autocorrelating a dark pulse train with low mark-to-space ratio. The pulse duration at half-maximum derived from Fig. 3*b* is 5 ps. As our cavity is not completely made up of PM components, the laser is subject to polarisation state instability, so that the pulse train is only stable on a timescale of a few seconds. In the future, we expect to be able to control this instability through the use of a shorter cavity and all PM components. The laser performance could be further improved through the use of a more elaborate fibre grating with the required symmetric two-peak characteristics, and a high-finesse intracavity Fabry–Perot filter for supermode noise suppression.

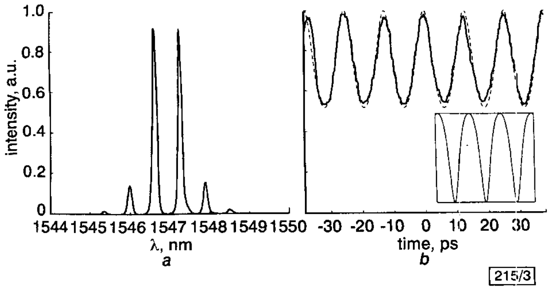

Fig. 3 *Laser output spectrum and corresponding autocorrelation trace for intracavity power of 62 mW*

Inset: pulse train with spectrum corresponding to experimental measurement in *a* assuming flat spectral phase
a Laser output spectrum
b Autocorrelation trace
– – – theoretical fit obtained from pulse train in inset

Conclusion: We have observed the generation of continuous-wave high-repetition rate dark pulse trains in an erbium-doped fibre laser that is passively modelocked by means of a dual-peak fibre Bragg grating filter. These preliminary results allow us to confirm for the first time the theoretical prediction of [7], which introduced the concept of DFWM as a passive modelocking mechanism, a technique that would potentially be useful for telecommunication applications.

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