Active Mode Locking of an Erbium-Doped Fiber Laser Using an Intracavity Laser Diode Device

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Abstract — A ridge waveguide, GaInAsP semiconductor laser chip has been used intracavity as a loss modulator in an erbium-doped fiber laser. Operating at modulation rates of around 500 MHz, typical pulse durations of 40 ps were obtained, with average output powers of up to 10 mW.

INTRODUCTION

As a result of their high gain, low insertion-loss characteristics in the region of lowest loss of silica based fibers, Erbium-doped fiber amplifiers have been the subject of considerable investigations [1]. Particular emphasis has been placed on their application to long distance, high bit rate communication [2], and to soliton amplification [3], [4].

In oscillator arrangements Erbium doped fibers present an attractive means of generating broadly tunable, high average powers [5], while the broad gain bandwidth [6] has been shown to be capable of amplifying solitons as short as 100 fs [7]. Active mode-locking of Erbium fiber lasers is therefore an attractive means of generating high repetition rate, wavelength tunable pulses for amplification, and nonlinear transmission studies.

The first reported mode-locking of an erbium-doped fiber laser utilized a bulk phase modulator, which generated relatively low-power pulses around 100 MHz repetition-rate [8]. Using an integrated fiber-coupled, lithium niobate amplitude modulator combined with soliton shaping, Kafka et al. [9] were able to generate pulses as short as 4 ps from their Erbium-doped fiber system. However, the pulse repetition-rates in this and a similar experiment [10] were around 40–100 MHz. Recently Takada et al. [11] obtained a pulse duration of only 8 ps at a repetition rate of 30 GHz, with average powers of 1–2 mW using a similar in-line modulator.

With relatively high average powers and high repetition rates obtainable from semiconductor diode lasers, these devices alone provide an attractive alternative. Integration, however, allows utilization of the high repetition rates available from semiconductor devices with the high power capability of the erbium fiber laser. Diode lasers provide a cheap and simple alternative to the in-line modulators used previously [9]–[11]. When no current is injected, the diode laser exhibits absorption, becoming transparent when carriers are injected as the forward current is increased. A short pulse drive signal can be readily produced allowing the device to operate as a fast modulator.

In this letter we describe the application of a GaInAsP ridge waveguide chip as a modulator in an erbium-doped fiber laser.

EXPERIMENTAL

The experimental configuration is shown in Fig. 1. A CW Argon ion laser operating at 514 nm was used as the pump source. The pump radiation was directed through a dielectric cavity mirror M which transmitted 90% at 514 nm and reflected 50% at 1.55 μm. Of the 2 W pump power available from the laser, up to 800 mW could be launched into the erbium-doped fiber via the 2 × 10 microscope objective MO1, which was antireflection coated in the 1.5 μm range.

The erbium-doped fiber was 3m long, with a outer diameter of 115 μm, a Δn of 0.008 and cutoff wavelength at 1.17 μm. At 1.55 μm the absorption was 8.8 dB/m and 90% of the pump radiation at 514 nm was absorbed over the 3 m length. In order to suppress sub cavity effects and to eliminate laser action off the fiber ends, quartz discs (W) with a 5° wedge were contacted with index matching gel to the fiber ends. Radiation exiting the fiber was collected and collimated using two ×10 microscope objectives MO2 and MO3 and focused into the laser diode chip (LD). The fiber laser output was taken via mirror M, and directed to the diagnostic and detection equipment using a dielectric beam splitter placed in the pump.

Fig. 1. Schematic of experimental arrangement.

Manuscript received May 1, 1990; revised May 29, 1990. A. V. Babushkin was financially supported by the Royal Society through an exchange agreement with the Soviet Academy of Sciences and P. G. J. Wigley was supported by a British Telecom-Science and Engineering Research Council CASE studentship.

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IEEE Log Number 9037741.
beam path which was nominally 100\% transmissive at 514 nm
and 100\% reflective at 1.5 \( \mu \text{m} \) for a 45\degree angle of incidence.

A GaInAsP semiconductor laser diode chip with a ridge waveguide structure (LD) formed the modulator. The device was 280 \( \mu \text{m} \) long, with one uncoated facet parallel to the other, which was 100\% reflection coated around 1.5 \( \mu \text{m} \). In the experimental configuration, this highly reflecting facet operated as the cavity end mirror in a linear arrangement. When run continuously as a laser at current levels of approximately 100 mA, the semiconductor device alone generated average output powers of 30 mW.

For pulsed operation, the amplified signal from a frequency synthesizer was used to drive a step recovery diode comb generator (Hewlett Packard 33004A) at 500 MHz, with an average power of 600 mW. The derived pulse train (RF) consisting of pulses with 90 ps duration was coupled into the diode via a bias-tee in conjunction with a variable dc drive current (DC).

**RESULTS AND DISCUSSION**

The overall fiber laser cavity, defined by mirror \( M \) and the highly reflecting facet of the laser diode, was initially arranged to have a cavity length 17 times that of the fundamental, determined approximately by the 500 MHz RF drive frequency supplied to the diode. With no dc bias current to the diode, laser action in the erbium fiber was suppressed. Increasing the dc bias current allowed lasing action to occur. The system was operated with a 20 mA dc bias current and a 600 mW RF drive signal. The laser diode could be driven at up to 150 mA forward current/halfway, at these levels self laser action would dominate. The dc current lasing threshold with no applied RF signal was at 45 mA.

At 20 mA, with 600 mW of RF applied, lasing action in the diode laser was not readily detectable; however, mode-locked operation of the erbium fiber laser was obtained. The output waveforms were detected on a Hamamatsu OOS-01/IR optical sampling oscilloscope, which incorporated a photocathode sensitive beyond 1.55 \( \mu \text{m} \) and had a temporal resolution of 10 ps. For a fixed cavity length, the RF drive frequency was adjusted in order to obtain minimum pulsewidth from the laser system. At a drive frequency of 500.475 MHz, routine operation with 40 ps pulse generation was achieved. Fig. 2 shows a typical output pulse of 37 ps recorded under these conditions. Varying the drive frequency by \( \pm 5 \text{ KHz} \) led to a measurable increase in the output pulse width. At optimum cavity match, the generated pulses were relatively symmetric with no evidence of secondary pulses or interpulse radiation.

The 0.1 nm spectral output from the optimized mode-locked laser is shown in Fig. 3. A transform limited 40 ps pulse at 1.531 \( \mu \text{m} \) requires a bandwidth of 0.06 nm, assuming a sech pulse shape, indicating operation well above the transform limit. An average power of 10 mW corresponds to a peak power of 0.5 W in the 40 ps pulses, while the fundamental soliton power for a 40 ps pulse in the erbium fiber is estimated to be 1.2 mW. This being the case, it would be expected that substantial pulse shortening could be observed by incorporating either intracavity or extracavity, optimized undoped fiber lengths for high order soliton compression. However, it is possible that the 280 \( \mu \text{m} \) diode laser device would operate as a bandwidth limiting element intracavity, but substantially shorter pulses could possibly be obtained by introducing a Brewster angle or placing an antireflection coating onto the uncoated facet. This would also enable substantially higher dc currents and RF modulation signals to be applied to the diode, without inducing diode self laser action.

The modulation rate used was limited by the available electronics. Potential modulation rates using the present structures would be several gigahertz and is determined by the structure of the devices. Other novel structures would permit substantially higher rates [12]. The carrier lifetime determines the upper limit on the modulation rates. However, depletion of the diode inversion by the intracavity flux of the optical pulse could give shorter pulses and possibly allow higher repetition rates.

**CONCLUSION**

We have demonstrated the active mode-locking of an erbium fiber laser using an intracavity semiconductor laser as a loss modulator. This technique has allowed the routine generation of 40 ps pulses, at a 500 MHz repetition-rate limited only by the available electronic driving circuitry. The Erbium laser has generated average powers of over 20 mW,
and this relatively inexpensive method of modulation has the potential to produce substantially shorter pulses and higher peak powers than the 40 ps and 0.5 W, respectively, demonstrated. Through using a pump laser with a higher average output power we have recently obtained peak power levels in excess of 1 W with essentially similar pulse widths. The laser should find applications to studies in high bit rate, nonlinear communication systems.

ACKNOWLEDGMENT

The provision of the erbium-doped fibers by B. J. Ainslie and S. P. Craig-Ryan of British Telecom Research Laboratories is gratefully acknowledged, as is the provision of the ridge waveguide laser diode by Dr. R. Gibb and G. Richards of STC Optical Devices, Paignton, Devon, and the loan of the Optical Sampling Oscilloscope by Hamamatsu UK Ltd.

REFERENCES