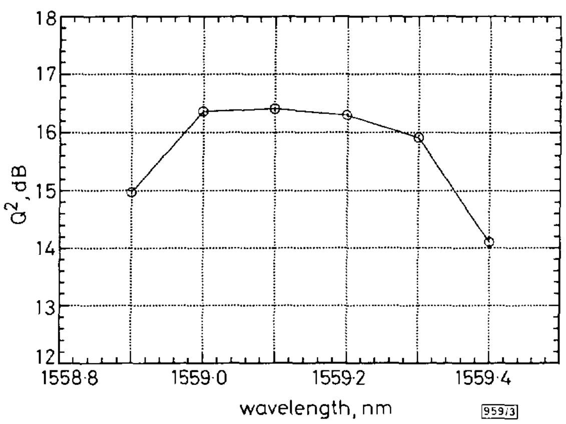

Fig. 3 *Q-window after 11300km transmission*

doped fibre amplifiers with 60km spacing using actual submarine cables and repeaters. The transmitted distance is the longest reported to date, as far as we know. Such performance may be attributed to the well-controlled manufacture and assembly process of the OS-A system, which has minimised the possible design offsets which cause system impairments. The results show the confidence of commercial service in ultra-long-haul optical cable systems using cascaded Er-doped fibre amplifiers.

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T. Otani, K. Goto, H. Abe, M. Tanaka, H. Yamamoto and H. Wakabayashi (*KDD Submarine Cable Systems Department, 2-3-2 Nishishinjyuku, Shinjyuku-ku, Tokyo 163-03, Japan*)

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Antiresonant Fabry-Perot quantum-well modulator to actively modelock and synchronise solid-state lasers

L.R. Brovelli, M. Lanker, U. Keller, K.W. Goossen, J.A. Walker and J.E. Cunningham

Indexing terms: Electro-absorption modulators, Laser modelocking, Solid-state lasers

The authors demonstrate active modelocking of an Nd:YLF laser using a semiconductor quantum-well reflectivity modulator as a cavity end mirror. The laser was modelocked at the fundamental frequency (100MHz) and at harmonics up to 1.6GHz. Synchronisation of passively modelocked pulses to an external RF signal was also demonstrated.

Modelocking of diode-pumped solid-state lasers has been a very active research area for the past several years. For many applications such as optical data communication, the laser pulses must be synchronised to an external RF signal, which can be obtained by active modelocking. Compared to semiconductor lasers, solid-state lasers offer the advantage that they can deliver much higher output powers in a diffraction-limited beam, as is needed, for example, in future computing systems employing thousands of optical interconnects. Active modelocking of solid-state lasers at gigahertz repetition rates has been demonstrated by several groups using both amplitude and phase modulators [1 – 3]. On the other side, quantum-well (QW) *pin* diode light modulators based on the quantum-confined Stark effect are used widely in various information processing systems which are currently under development.

In this Letter we demonstrate for the first time the use of an MQW modulator as an intracavity amplitude modulator to actively modelock a solid-state laser. With a diode-pumped Nd:YLF laser we have achieved modelocking up to the 16th harmonic, corresponding to a repetition rate of 1.6GHz. Within an all-solid-state ultrafast laser technology, semiconductor QW modulators seem promising, because they have the advantages that they are compact, inexpensive, fast, and can cover a wide wavelength range from the visible to the infra-red regions. In addition, they only require a few volts of drive voltage or a few hundred milliwatts of RF power. In general, however, semiconductor QW modulators would introduce too high losses in a solid state laser cavity and have too low a damage threshold. Similar problems have been solved for the case of an intracavity semiconductor saturable absorber by use of the recently developed antiresonant Fabry-Perot saturable absorber (A-FPSA), which integrates the semiconductor absorber inside a Fabry-Perot cavity that is operated at antiresonance [4, 5]. The intensity inside the semiconductor absorber therefore is much lower than the incident intensity, thus increasing the damage threshold and decreasing the insertion losses. The A-FPSA, used as an end mirror in a laser cavity, has successfully passively modelocked many different solid-state lasers. In this Letter we extend this principle to an active QW modulator to actively modelock and synchronise an Nd:YLF laser.

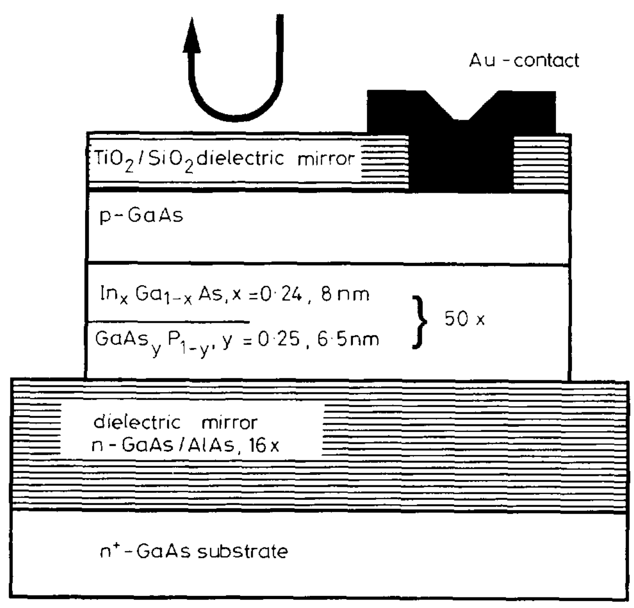

Fig. 1 *Structure of antiresonant Fabry-Perot MQW modulator designed for operation wavelength 1.047μm*

The QW modulators we used (Fig. 1) are the recently demonstrated pseudomorphic InGaAs/GaAsP MQW modulators [6] in which the introduction of phosphor into the barriers leads to a smaller lattice constant than that of GaAs, balancing the strain induced in the InGaAs wells. In this way the material does not relax during growth, and the surface is optically smooth. The pseudomorphic structure was grown by gas source molecular beam epitaxy using cracked arsine and phosphine. A 16-period *n*-type GaAs/AlAs quarter-wave mirror was grown, followed by a 50-period $In_{0.24}Ga_{0.76}As/GaAs_{0.25}P_{0.75}$ intrinsic MQW. Finally, a 0.5μm-thick *p*-type GaAs layer was grown. After growth, a 4-period SiO_2/TiO_2 quarter-wave mirror was evaporated with about

95% reflectivity, forming a Fabry-Perot cavity together with the GaAs/AlAs mirror. Using a reactive ion etch of SF_6 and O_2, the high-reflectivity coating was removed locally to open windows for the 50 × 100μm² gold contacts, which were then deposited. Finally, 200 × 200μm² mesas were etched. The total thickness of the MQW absorber and the *p*-type GaAs layer were designed to give an antiresonance of the Fabry-Perot cavity at the desired wavelength (1.047μm), i.e. a broad maximum of the reflectivity. The free spectral range of the modulator, i.e. the useful spectral range between two resonances, was 80nm. In contrast to the sharp resonance, the antiresonance provides loose design tolerances for the optical thickness of the modulator, which is therefore insensitive to small variations induced, for example, by heating effects. The modulators then were mounted on copper mounts and connected through bond wires to 50Ω connectors. The reflectivity of the modulator with no applied bias was calculated to be approximately 99%, thus introducing not more than 1% insertion losses, and the change in reflectivity obtained by modulating the bias from 0 to −10V was measured to be in the order of several tenths of a per cent, which was sufficient to actively modelock an Nd:YLF laser.

For the modelocking experiments we have built a diode-pumped gain-at-the-end Nd:YLF laser with a cavity design very similar to that used for passive modelocking experiments using an A-FPSA [7]. The laser mode was focused to a spot diameter of approximately 60μm on one modulator-mesa that replaced one of the end mirrors of the linear folded cavity. A 1% output coupler replaced a folding mirror of the laser cavity, thus leading to two output beams. The pump was a 1.2W, 100 μm-wide diode laser array at 798nm wavelength focused into the Nd:YLF crystal with a spot radius of 30μm by 100μm, whereas the beam radius of the laser mode was 40μm by 50μm. The length of the cavity led to a fundamental modelocked repetition rate of 100MHz.

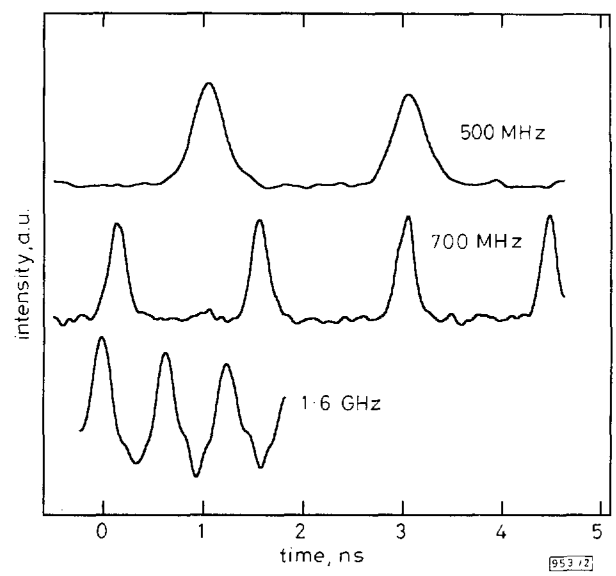

Fig. 2 *Modelocked pulse trains at 500MHz, 700MHz and 1.6GHz observed with sampling oscilloscope*

To actively modelock the laser, an amplified RF signal superimposed to a DC bias of −4.1V was applied to the modulator. The voltage amplitude was 9 V_{pp}. We measured the pulses using a sampling oscilloscope (20GHz) together with a fast photodetector (Fig. 2). We obtained modelocked pulses at RF frequencies up to 1.6GHz limited by the length of the wiring bonds. The pulse duration at 700MHz (7th-order) was 200ps and showed no further decrease for 1.6GHz (16th-order). The maximum average output power for which pure active modelocking was obtained was 27mW for one beam and was limited by the onset of passive *Q*-switching or passive modelocking due to absorption saturation of the modulator.

One advantage of QW modulators compared to other modulators such as acousto-optic modulators or phase modulators is that they can also act as saturable absorbers leading to passive modelocking with much shorter pulses. Combining the effects of saturable absorption and absorption modulation with one single device we demonstrate the possibility to synchronise passively modelocked pulses to an external RF signal. To obtain the highest small-signal gain for the best passive modelocking we replaced the pump diode by a Ti-sapphire laser with a minimum beam radius of 15μm in the crystal. The new cavity had a repetition rate of 135 MHz. We measured the pulsewidth with the sampling oscilloscope using the RF signal as trigger source. This showed clear pulses only when the pulses and the trigger signal were synchronised. For low output powers in the order of 20mW per beam, the measured pulse duration was 300ps, and the pulses remained synchronised to the trigger over a change in frequency of several hundred hertz.

To conclude, active modelocking of an Nd:YLF laser using an InGaAs/GaAsP MQW modulator has been demonstrated up to 1.6GHz. This result can be improved by optimising the samples with respect to high-speed modulation. For higher output powers where absorption bleaching starts to dominate the modulation, active modulation of the antiresonant Fabry-Perot modulator is no longer the dominant modelocking mechanism. However, we have shown that the pulses in this case can still be synchronised to an external RF signal without the need for an active cavity length control [8]. Furthermore, we can easily extend this technology to longer wavelengths by the use of quaternary materials on InP to modelock lasers with, for example, erbium-doped crystals, which is of considerable interest for optical data communication.

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L.R. Brovelli, M. Lanker and U. Keller (*Swiss Federal Institute of Technology, Institute of Quantum Electronics, CH-8093 Zurich, Switzerland*)

K.W. Goossen, J.A. Walker and J.E. Cunningham (*AT&T Bell Laboratories, Holmdel, NJ 07733, USA*)

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