operation. These results indicate that GaAs-based devices with GaInNAs as the active layer material may be used as light sources for the E-band in low-water-peak fibre systems. Furthermore, our results strongly encourage the investigation of GaInNAs devices for the 1.55 µm region.

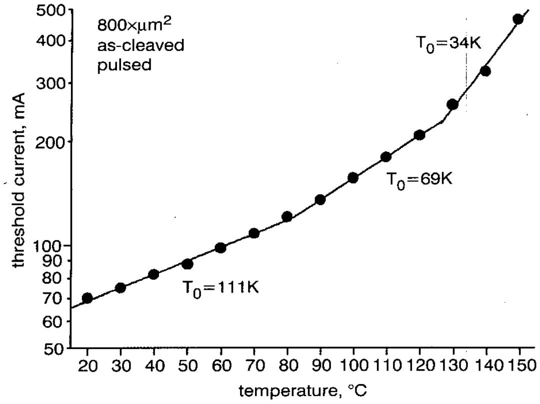

Fig. 3 *Temperature dependence of threshold current under pulsed operation of As-cleaved 800 × 4 µm² ridge laser*

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D. Gollub and M. Fischer (*Nanoplus Nanosystems and Technologies GmbH, Oberer Kirschberg 4, 97218 Gerbrunn, Germany*)

E-mail: dirk.gollub@nanoplus.com

S. Moses and A. Forchel (*Universität Würzburg, Technische Physik, Am Hubland, 97074 Würzburg, Germany*)

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Multi-wavelength source with 25 GHz channel spacing tunable over C-band

G.J. Spühler, P.S. Golding, L. Krainer, I.J. Kilburn, P.A. Crosby, M. Brownell, K.J. Weingarten, R. Paschotta, M. Haiml, R. Grange and U. Keller

A compact, passively fundamental-modelocked Er:Yb:glass laser with 25 GHz pulse repetition rate tunable over the C-band is demonstrated. By combining this laser with a dynamic gain equaliser, a flat optical spectrum with up to 36 discrete channels with a 25 GHz spacing and an optical signal-to-noise ratio >40 dB was generated.

As data transmission rates and the number of WDM transmission channels steadily increase, pulsed lasers are becoming increasingly important for telecom applications. Looking in the time domain, modelocked lasers are well known to produce a train of short pulses with a high contrast ratio and low timing jitter. Such characteristics are highly desirable in next generation optical-time-division-multiplexing (OTDM) systems. In the wavelength domain, fundamental-modelocked lasers generate a stable comb-shaped optical spectrum, where the spacing of the longitudinal modes exactly equals the pulse repetition rate and shows a high optical signal-to-noise ratio (OSNR). Therefore, pulse-generating lasers (PGLs) are intrinsically wavelength-stable multichannel sources which can be used as comb-generating lasers (CGLs) in dense wavelength-division-multiplexing (DWDM). Varying the cavity length and comparing/locking a single longitudinal mode of the laser to an ITU grid line or any other reference, the entire optical comb of the CGL is automatically locked to the ITU grid. This turns the CGL into a novel and simple multi-wavelength source, ideally suitable for DWDM network and test and measurement applications. The distinct channels of the CGL can be separated with appropriate means, individually modulated and recombined to launch into the network [1]. Compared to the classic DWDM approach with one fixed-wavelength-laser per channel, the CGL approach brings many benefits to the system, such as decreased number of components (i.e. only one laser and one wavelength locker are required), better power budget, smaller inventory and space requirement, etc.

Passively modelocked, optically-pumped solid-state lasers have been presented with repetition rates up to 159 GHz in the 1 µm wavelength regime [2]. Recently we presented a passively modelocked Er:Yb:glass laser, emitting picosecond pulses with a repetition rate of 10 GHz and sub 100 fs rms timing jitter, tunable over the C-band [3, 4]. In this Letter, we demonstrate a multiwavelength source for the 25 GHz ITU grid in the C-band based on a similar approach, a tunable passively fundamental-modelocked 25 GHz Er:Yb:glass laser. We combine this CGL with a dynamic gain equaliser (DGE) and an erbium-doped fibre amplifier (EDFA) to prove the suitability of the CGL for DWDM applications.

For many reasons, Er:Yb:glass is well suited for telecom applications. Its gain bandwidth covers the entire C-band, it can be pumped with standard 980 nm laser diodes used in EDFAs, and it is robust and low-cost. However, its small emission cross-section typically limits the ability to achieve passive modelocking at high repetition rates without Q-switched modelocking (QML), a regime where the modelocked pulse train is underneath a lower frequency Q-switch-envelope [5]. To overcome this limitation, we have designed a novel semiconductor saturable absorber mirror (SESAM) [6, 7], allowing us to minimise the saturation influence of the saturable absorber and to custom design its modulation depth. The Er:Yb:glass gain element and the saturable absorber are inserted into a cavity which is designed for minimised mode areas in the gain element and in the absorber in order to suppress QML (Fig. 1). The total cavity length is below 6 mm and the laser operates with fundamental-modelocking, i.e. there is only one laser pulse circulating in the resonator. This avoids sub-harmonics in the optical spectrum that typically decrease the OSNR in harmonically modelocked lasers. Compared to actively modelocked fibre lasers or semiconductor lasers, no RF signal is required to generate the pulse train and thus the spectral comb. The laser is end-pumped with 400 mW from a fibre-coupled 980 nm laser diode, allowing for optimum mode matching. The average output power is up to 25 mW, the pulse duration 1.9 ps, and the FWHM of the optical spectrum 3.1 nm. We measured a contrast ratio exceeding 30 dB. With an angle-tuned intracavity etalon (Fig. 1) the laser can be continuously tuned from 1528 to 1561 nm. Fig. 2 shows the pulse duration and the QML threshold (required output power to suppress QML) against the centre wavelength of the laser as well as a few spectra. The main laser parameters do not change strongly while tuning over the C-band.

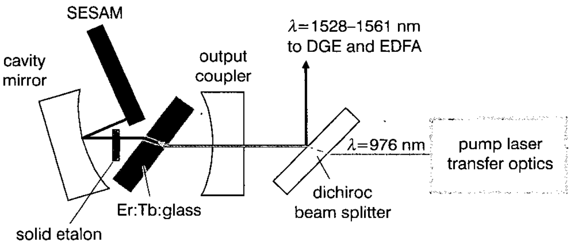

Fig. 1 *Schematic diagram of cavity*

SESAM: semiconductor saturable absorber mirror; DGE: dynamic gain equaliser; EDFA: erbium-doped fibre amplifier

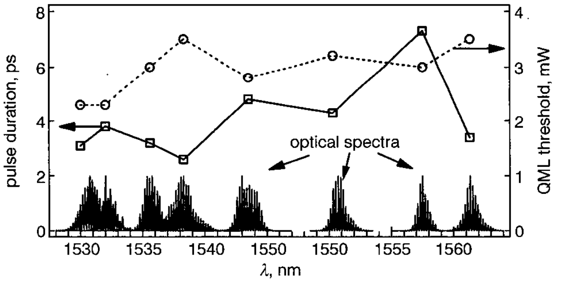

Fig. 2 *Measured pulse duration and average output power at QML threshold against operation wavelength set with etalon; corresponding optical spectra also shown*

——□—— measured pulse duration against operation wavelength
·····○····· QML threshold against operation wavelength

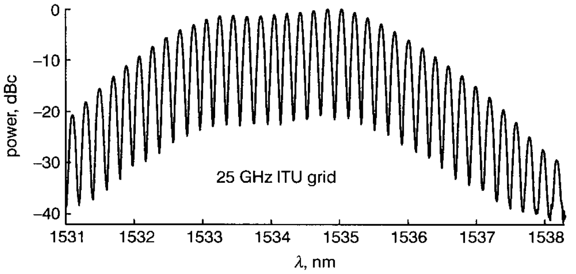

Fig. 3 *Optical spectrum of laser manually tuned to ITU grid*

Resolution bandwidth of only 0.07 nm limits visible OSNR

Tilting the etalon moves the envelope of the spectrum across the C-band, whereas changing the cavity length moves the individual longitudinal modes underneath the envelope. In this way, the comb spectrum can be tuned to any desired wavelength in the C-band, i.e. to the ITU grid, essentially without changing the grid spacing. The reason for this is that the carrier frequency is several orders of magnitude higher than the repetition rate. Therefore, a sub-wavelength change in cavity length has only a minimum impact on the channel spacing. With a 25 GHz channel spacing, the maximum frequency offset between a longitudinal mode and a required reference line is 12.5 GHz. To remove this offset, the cavity length has to be changed by a quarter wavelength leading to a change in repetition rate (and thus channel spacing) of only 1.6 MHz, which is well below the tolerance of the ITU channels and typical bandwidths of DFB lasers. Fig. 3 shows a sample spectrum of the 25 GHz laser manually tuned to the ITU grid lines around 1534 nm.

Fig. 4*a* shows the optical spectrum of the CGL without the etalon but in conjunction with a dynamic gain equaliser (Silicon Light Machines, Model:SLM2200). The DGE allows setting of the attenuation of each channel individually and in real time. Using the maximum dynamic range of the DGE (17 dB), up to 36 channels with a flatness <0.5 dB could be generated with an OSNR exceeding 40 dB (resolution bandwidth 0.01 nm). Adding an EDFA to the system and readjusting the DGE, we could get up to 25 channels with 10 dBm each, and an OSNR exceeding 35 dB (Fig. 4*b*). No additional filters have been used to suppress the amplified spontaneous emission of the EDFA. One single wavelength locker with an appropriate feedback circuit controlling the cavity length would allow locking of all these channels to any reference. Keeping in mind the simplicity of the presented system, the potential of such a passively modelocked laser as a source for DWDM system applications becomes clear. An additional stage for supercontinuum generation, i.e. an amplifier and a specially designed fibre section, could increase the number of obtained channels substantially [1] and would benefit from the spectral purity and stability of the presented laser.

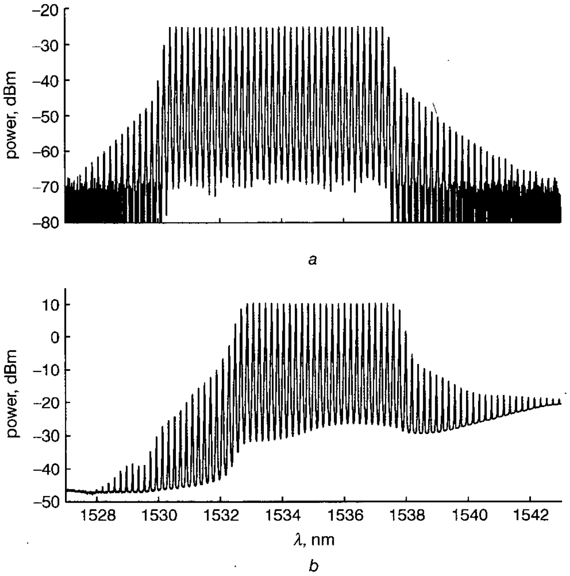

Fig. 4 *Optical sepectra*

a Optical spectrum of CGL flattened with DGE. There are 36 channels with a flatness of 0.5 dB and an OSNR of 40 dB

b Optical spectrum of system CGL, DGE, EDFA. There are 25 channels with 10 dBm each. Resolution bandwidth 0.01 nm

Conclusion: We have presented a simple passively modelocked laser tunable over the C-band with a pulse repetition rate of 25 GHz. With a dynamic gain equaliser, we obtained up to 36 channels spaced by 25 GHz and with <0.5 dB deviation from flatness of the channels. By adding an EDFA to the system, 25 channels with 10 dBm/channel have been obtained. The OSNR of the spectrum always exceeded 35 dB.

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G.J. Spühler, P.S. Golding, L. Krainer, I.J. Kilburn, P.A. Crosby, M. Brownell and K.J. Weingarten (*GigaTera, Inc., Lerzenstrasse 16, CH-8953 Dietikon, Switzerland*)

E-mail: gabriel.spuehler@gigatera.com

R. Paschotta, M. Haiml, R. Grange and U. Keller (*Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg—HPT, CH-8093 Zürich, Switzerland*)

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Cryogenic opened cavity sapphire resonator for ultra-stable oscillator

P.Y. Bourgeois, Y. Kersalé, N. Bazin, M. Chaubet and V. Giordano

A new high-*Q* sapphire whispering gallery mode resonator is proposed to achieve ultra-high frequency stability. It is proposed to use the sapphire resonator without metallic walls to suppress spurious modes perturbating the main resonance. Providing the azimuthal order of the chosen whispering gallery mode is sufficiently high, *Q*-factors better than 2×10^8 have been observed, which turn out to be sufficient to reach a high frequency stability. A first oscillator prototype operating at 12 GHz shows a relative frequency instability of 3×10^{-14}.

Introduction: For integration times ranging from 0.1 to 1000 s cryogenic sapphire oscillators (CSOs) achieve the best frequency stability that is feasible nowadays. A sapphire resonator usually consists of a disk machined in a low defect Al_2O_3 monocrystal in which whispering gallery modes are excited. These resonance modes are characterised both by high *Q*-factors and a low sensibilities to temperature fluctuations [1]. CSOs presenting frequency stability better than 1×10^{-15} have been reported already [2].

To prevent radiation losses, ensure thermal shielding and enable stable mechanical mounting of resonator access, the sapphire disk is generally placed in the centre of a cylindrical metallic cavity made in copper or niobium. In such a structure, whispering gallery modes can be swamped with a number of high-order spurious modes resulting from cavity resonance modes perturbed by the sapphire disk. Spurious modes can induce *Q*-factor degradation and thermal sensitivity enhancement of the main resonance. Moreover, they make the coupling adjustment of the resonator difficult to achieve. Indeed, changing for example the location of a probe in the cavity changes the coupling coefficient of the main resonance but at the same time modifies the configuration of the spurious modes nearby. Resonator adjustment is a trade-off between setting the right coupling coefficient for the main resonance and reducing the influence of the spurious modes. Providing skills and good luck, this trade-off can be barely obtained for a few whispering gallery modes before cooling down. Furthermore, as frequency and coupling vary greatly during the cooling, initial adjustment can be drastically altered at low temperature. In this Letter we demonstrate that the metallic cavity cylindrical wall can be removed without drastically altering the high-order whispering gallery mode *Q*-factor. Low *Q* spurious modes are totally suppressed, making the resonator coupling adjustment easier. High frequency stability is demonstrated in a preliminary prototype using this simple resonator structure.

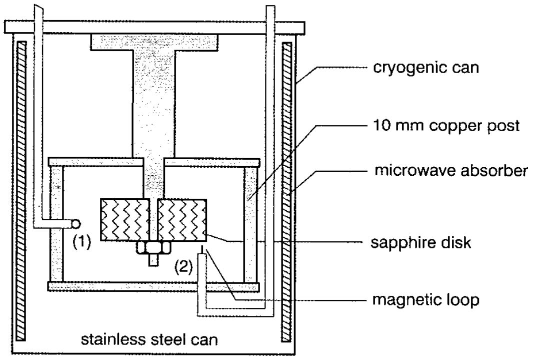

Fig. 1 *Cryogenic insert*

Cryogenic opened cavity sapphire resonator: Fig. 1 is a schematic diagram of our resonator structure. The 50 mm diameter and 20 mm high sapphire disk is supported by a copper post directly fixed to the top flange of the cryogenic insert. Thermal sensors and heaters are anchored in this copper post for thermal regulation. Two copper lids limit the axial resonator dimension. The lids are thermally connected by four 10 mm diameter copper posts. Two small magnetic loops enable one to excite the quasi-transverse magnetic field (WGH) mode family. The probe 1 generates an azimuthal magnetic field H_φ. Probe 2 anchored in the bottom lid excites a radial magnetic field H_ρ. This ensemble is placed in the cryogenic can, the internal walls of which are covered with microwave absorber sheets.

The cryogenic can placed in a large helium dewar and then cooled to 4.2K. Two 1.5 m length semi-rigid cables connect the cryogenic resonator to the electronic circuit placed at room temperature. The open cavity reveals itself very efficient to suppress spurious modes. Each WGH family mode appears clearly defined over more than 500 MHz frequency span. The transmission peaks are superimposed to a nearly flat background 40 to 50 dB lower and *Q*-factors as high as 500 million have been observed.

Oscillator performances: We chose to operate on the $WGH_{17,0,0}$ mode at 12 GHz for which, in our first attempt, coupling coefficients have been revealed well adjusted ($\beta_1 \simeq 0.9$ and $\beta_2 \simeq 0.05$). The temperature has been stabilised at the turnover temperature of $WGH_{17,0,0}$ mode equal to 6K. Pound servo with 50 kHz modulation frequency has been implemented to correct the phase variations in the oscillator circuit [3]. In this first prototype the circulator enabling one to extract the reflected signal from the resonator has been placed at