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Compact low-noise pulse generating lasers with repetition rates of 10 to 50 GHz

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We review the main results obtained with our recently introduced passively fundamental mode-locked Er:Yb:glass lasers mainly in the context of telecom applications, and we discuss their key enablers. Specifically, we focus on the aspects of the lasers for application in the time-domain for optical time-division multiplexing and in the wavelength domain for dense wavelength-division-multiplexing.

Keywords: Solid-state laser; passive mode locking; high pulse repetition rate.

1. Introduction

There are many compelling reasons to use return-to-zero (RZ) formats [1,2] and/or soliton dispersion management techniques [3,4] for novel transmission systems at 10 Gb/s, 40 Gb/s and higher bit rates per channel. These techniques rely on clean optical pulses and thus benefit greatly from the availability of simple, compact, low-noise and efficient optical pulse generators. Therefore, pulsed lasers are becoming increasingly important for telecom applications as data transmission rates continue to increase. There are many reasons to use a pulsed laser directly as a source in the transmitter of optical telecommunication systems, rather than an externally modulated cw source. Pulsed lasers eliminate the need for a high-end modulator to create the pulses and thereby simplify system architecture, increase efficiency, and reduce cost. Furthermore, the contrast ratio of pulsed lasers is typically much higher than for modulated cw sources. This improves system signal-to-noise and allows for further scaling to higher bit rates through optical time-division multiplexing (OTDM). Apart from the transmitter side, there are interesting applications of pulsed lasers also in the receivers of transmission systems, e.g. for demultiplexing and clock recovery [5-7]. In addition, pulse generating lasers (PGLs) can be used as multi-wavelength sources for dense wavelength-division-multiplexing (DWDM) systems [8,9]. Furthermore, there are applications outside the telecom area, in the fields of optical clocking [10,11], high-speed electro-optic sampling [12,13], frequency metrology (similar to the work presented in Ref. [14]) or generation of polarized electron beams for particle accelerators [15].

The following requirements have to be fulfilled for an ideal pulse generating source for telecom applications: Besides a repetition rate that is matched to the standards for 10, 40 Gb/s or higher transmission rates [16], reasonable average output power, low timing jitter, high contrast ratio and wavelength tunability in the regime of interest (mostly in the C-band from 1530 – 1565 nm) are required. The requirement for the pulse duration depends on the coding format. Usually the full width at half max (FWHM) of the pulses should be around a third of the bit period. Besides these requirements on the optical properties of the pulse train, high efficiency, compactness, simplicity, reliability and a cost-saving manufacturing process are important features for a telecom product.

In the past, pulse sources with pulse repetition rates of several GHz almost always involved either an edge-emitting semiconductor laser [17], which is usually actively or hybrid mode-locked, or a harmonically mode-locked fiber ring laser [18]. Edge-emitting semiconductor lasers appear very attractive due to their very compact and stable optical setup. However, the average optical output power is typically rather low and the timing jitter can be relatively high, degrading transmission at high bit rates. The increased timing jitter is explained by rather high cavity losses and a low average power [19]. Furthermore, these lasers often require a large amount of RF drive power for stable operation and are susceptible to satellite pulses generated at intracavity surfaces. Multi-GHz fiber lasers can easily generate high-quality pulses with good output power and low timing jitter. However, fiber lasers typically need to have a cavity length of several meters in order to get good pump absorption, gain, and thus efficient operation. Therefore sophisticated means are required to obtain stable harmonic mode locking with a large number of precisely equidistant pulses in the cavity. The individual pulses generated by harmonic mode locking do typically not exhibit a fixed phase relation. This excludes certain promising coding formats such as return-to-zero differential phase shift keying [20,21] which carry the data in the phase of the pulses, rather than in the amplitude. Additionally, also the typical fiber ring laser used for telecom applications makes use of an intracavity modulator which requires a large amount of RF power.

Here, we report on our recently developed alternative pulse sources for telecom applications, based on passively fundamental mode-locked solid-state lasers. Passive mode locking totally eliminates the use of a modulator and thus drastically reduces the demand on RF power. Only a rather weak RF signal (typically several orders of magnitude less than for driving a modulator) is required for feeding a phase-locked loop that keeps the cavity length of the passively mode-locked laser constant. Additionally, the typical diode-pumped passively mode-locked solid-state laser uses a rather low-loss cavity due to the limited small signal gain and the need to suppress Q-switched mode locking [22]. This leads intrinsically to low timing jitter, provided that a stable laser cavity setup is used. Fundamental mode locking in the multi-GHz regime leads to very compact cavity setups that can be implemented very ruggedly.

In the last millennium, the repetition rate of passively mode-locked solid-state lasers has been limited to a few GHz [23]. Especially in the telecom wavelength regime, where only few solid-state gain media are available cw-mode locking with multi-GHz pulse repetition rates have not been possible [24,25]. In recent years, the consequent exploitation of the flexibility of semiconductor saturable absorber mirrors (SESAMs) [26-28] in combination with increased understanding of the limitations [22,29-32] of cw mode locking allowed us to develop passively mode-locked lasers with multi-GHz pulse repetition rates, very good pulse quality, comparatively high output powers and wavelengths in the regime of interest. Passive mode locking implies that the pulses are achieved without using any multi-GHz electronics. Fundamental mode locking leads to ultra-compact cavity setups and to the fact that every output pulse is a copy of the same single pulse bouncing back and forth in the cavity. Therefore, pulse-to-pulse variations are minimized and the output pulses have a fixed phase relation.

In this paper we limit our discussion to the 1.5 μm wavelength regime. However, much progress has also been achieved at other wavelengths, important for different applications as for example optical clocking. A recent review paper gives more information with respect to that [33].

2. Er:Yb:glass

The choice of solid-state gain media in the wavelength regime of interest is rather limited. Mainly Er:Yb:glass and Cr:YAG are used. The latter has very strict requirements on the pump source due to its weak pump absorption and it exhibits relatively low efficiencies, because of limited crystal quality and relatively high induced losses [34,35]. Therefore, the so far most successful gain medium for a multi-GHz passively mode-locked solid state laser in the telecom wavelength regime is Er:Yb:glass, although it has very small cross sections and thus a strong tendency towards Q-switched mode locking (QML) [22]. The way we overcome these limitations is explained in Section 3. Generally, Er:Yb:glass is well suited for telecom applications. Its gain bandwidth covers essentially the whole C-band [36] and allows for ultrashort pulse-generation [37], it can be efficiently pumped with standard telecom-grade 980-nm laser diodes also used in erbium-doped fiber amplifiers (EDFAs), it can be produced in excellent quality and large amounts, and it is resistant and cheap. An alternative way to reach the 1.5-μm regime is to use nonlinear processes. Synchronously pumped optical parametrical oscillators (OPO) [38,39] are powerful tools, which give higher power levels and wider tuning ranges at the cost of increased complexity, reduced stability and efficiency.

3. Challenges – Q-switched mode locking (QML)

Passively mode-locked solid-state lasers typically have a pulse repetition rate of a few hundred MHz. For fundamental mode locking, the inverse pulse repetition rate is given by the time a pulse needs for one round-trip in the laser cavity. The shorter the resonator the higher the repetition rate - and (for constant average output power) the smaller the intracavity pulse energy. As mentioned, the main challenge one has to face when pushing the repetition rate of a passively mode-locked laser to the multi-GHz regime, is the suppression of QML. QML is a state of operation where the relaxation oscillations are destabilized; the damping effect for increased intracavity powers due to gain saturation is not strong enough to suppress the growth due to increased saturation of the absorber. A high repetition rate naturally leads to relatively low intracavity pulse energies which limit the saturation of the gain and thus increases the tendency for QML. In addition, Er:Yb:glass exhibits rather small cross sections and has thus a high saturation energy which again increases the tendency towards QML.

In order to suppress QML in our Er:Yb:glass lasers we rely on the following concepts: The SESAM allows to custom design the main absorber parameters within a certain range, mainly by adopting the structure of the device and its composition [27,40]. We exploit that range for minimized saturation fluence and modulation depth which both helps to suppress QML [22]. Furthermore, we make use of a roll-over in the saturation curve of our SESAMs. The reflectivity of a semiconductor SESAM is generally expected to increase with increasing pulse energy. However, for higher pulse energies the reflectivity can decrease again and exhibit a roll-over in the nonlinear reflectivity curve caused by inverse saturable absorption [31]. This effectively increases the losses for pulse fluences above this roll-over point and acts as a pulse energy limiter and thus helps to suppress QML [30].

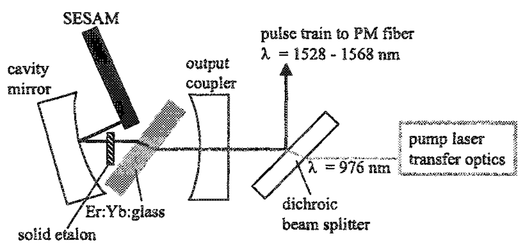

Fig. 1 Setup of the 10-GHz Er:Yb:glass laser. Cavity length ≈ 14 mm. 50-GHz laser has similar setup with cavity length ≈ 3 mm and without etalon.

For fundamental mode locking, the repetition rate dictated by the application determines the cavity length. With the constraint of the length of the cavity and the SESAM being a flat end mirror of the laser, we designed the cavity in such a way that its mode size on the SESAM in combination with intracavity pulse energy leads to a pulse fluence on the absorber which is close to the roll-over point. The mode size in the gain medium is minimized taking into account the pump beam quality and the thickness of the gain element, leading to a simple three-mirror-cavity as shown in Fig. 1. This cavity setup minimizes the saturation energy of the gain and maximizes the efficiency and the exploitation of the inverse saturable absorption insuring the suppression of QML. The laser glass is inserted into the cavity under Brewster's angle to induce linear polarization and minimize intracvity losses. A further important point is the use of a single-mode 980-nm pump diode. It enables optimum mode matching of pump and laser mode even though the laser mode size in the gain is very small. This allows for good efficiency and excellent mode quality.

With this approach of diode-pumped passively fundamental mode-locked Er:Yb:glass lasers, we have presented pulse repetition rates up to 50 GHz. Fig. 1 shows the cavity design. For a 10-GHz laser the total cavity length is 14 mm, and for the 50-GHz cavity it is as short as 3 mm.

4. Results

4.1. Time domain

In time domain applications, the user is mainly interested in the temporal evolution of the output of the laser: Pulse repetition rate, pulse duration, extinction ratio, timing jitter, etc. Each pulse is used for a special purpose: to carry information [41] or to induce some switching window [7] or for other processes. The center wavelength and width of the optical spectrum as well as its purity are of interest too, especially for systems with multiple channels.

4.1.1. 10-GHz pulse generating lasers

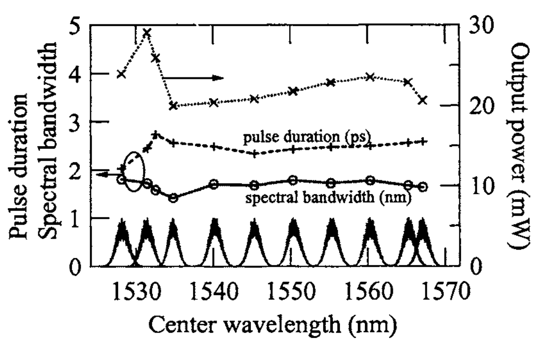

Fig. 2 Pulse duration (dashed), spectral bandwidth (solid) and output power (dashed-dotted) as a function of center wavelength for a 10-GHz Er:Yb:glass laser together with several sample spectra.

Fig. 1 shows the cavity set up for a 10-GHz PGL, as explained in section 3. Next to the SESAM and the Er:Yb:glass gain element, the cavity contains a solid etalon to select the center wavelength. Varying the SESAM parameters and the intracavity filter effect from the etalon, pulse durations from 1 to 19 ps could be obtained [42,43]. With the etalon the laser wavelength can be adjusted within 1528 – 1568 nm (full C-band) by tuning the tilt angle (Fig. 2). During tuning, only week variations of the main laser parameters, such as pulse duration, spectral bandwidth and average power are observed [43]. We typically couple the output of the laser into a polarization-maintaining fiber where we get 10 to 20 mW of average power with a polarization extinction ratio of >20 dB for a pump power of about 250 mW.

The output pulse train is charcterized by a very high contrast ratio of typically >30 dB and a very stable optical spectrum (Fig. 3). Fig. 3a shows a high dynamic range autocorrelation with a scan range exceeding the pulse separation. This reveals the first cross correlation. The highest signal between the pulses is 36 dB below the carrier showing the excellent contrast ratio that can be achieved with these lasers. The measurement is shown together with a Gaussian and a $sech^2$ fit, indicating that the measured pulses are fitted better by a Gaussian pulse. In order to show the suitability of the Er:Yb:glass laser for transmission at high bit rates, we show in Fig. 4 an autocorrelation of a pulse train which has been obtained by optical time division multiplexing (OTDM) of a 10-GHz laser up to 160 GHz with commercially available multiplexers (PriTel Inc., OCM-4). First of all, we can see that the pulses are short enough (in this case ≈1 ps) for such a high bit rate. Secondly, the contrast ratio is high enough even for 160 Gb/s transmission to avoid a significant noise level between the multiplexed pulses.

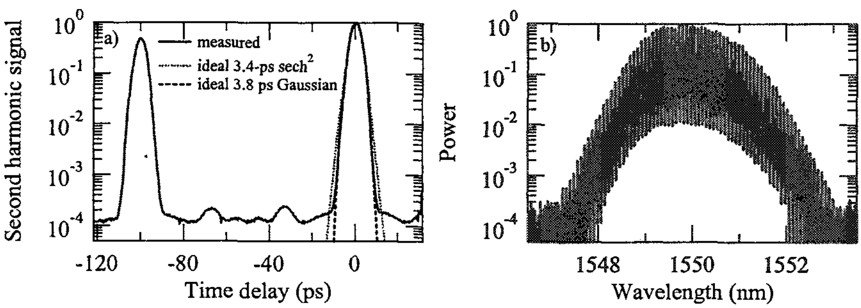

Fig. 3 a) Slow scan autocorrelation. The autocorrelation scan range exceeds the pulse separation. Maximum signal level between the pulses is –36 dBc. The Gaussian fits the measured autocorrelation trace better than the autocorrelation of a $sech^2$ pulse. b) Typical optical spectrum of a 10-GHz Er:Yb:glass laser taken with a resolution of 0.01 nm resolving the individual longitudinal modes.

Of further importance for transmission systems with such high bit rates is synchronization of the pulses of the PGL to an existing clock signal with very low phase noise. This synchronization is naturally given for actively or hybrid mode-locked lasers, at the price of the need for an intracavity high speed modulator, which requires a lot of drive power. A passively mode-locked laser does not need any active mean to generate the pulses, but to synchronize them to the clock signal. This can be done by a simple phase-locked-loop (PLL), which locks the cavity length to the clock signal [44,45]. This approach of passive mode locking – active synchronization has several advantages: The amount of power required from the clock is orders of magnitude smaller than required for a modulator and the simplicity of the pulsing mechanism allows the clock signal to drift within a certain range while the laser remains phase locked. This flexibility is beneficial for applications in the receiver end of a transmission system, as during transmission the clock signal can be deteriorated significantly [7]. For synchronization to an external clock signal, we mount the SESAM on a piezo element. A small part of the output signal is tapped and its phase is compared to the one of the clock signal. The error signal is amplified, filtered and fed back to the piezo element to adjust the cavity length for minimum phase deviation. With a relatively low loop bandwidth of less than 20 kHz, we regularly obtain rms timing jitter values below 80 fs, when integrating the phase noise power spectral density measured with the von der Linde technique [46] from 10 Hz to 1 MHz (Fig. 5). The measurement is mainly limited by the noise of the local oscillator of the microwave spectrum analyzer rather than the laser itself. The measured phase noise is by far low enough to perform transmission experiments at 160 Gb/s [41]. As we apply fundamental mode locking, there are no supermodes.

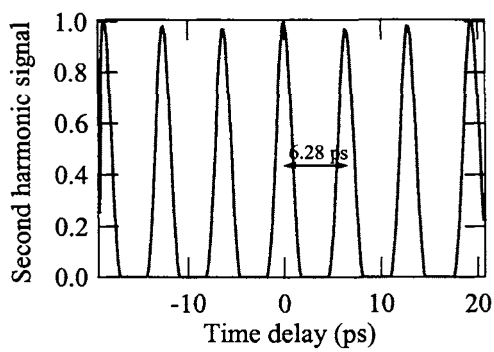

Fig. 4 Autocorrelation trace of a pulse train multiplexed from 10 GHz to 160 GHz.

Recently, the theory of noise of mode-locked lasers has been investigated in detail by Paschotta [19,47]. In an ideal case, the mechanical and electrical implementation of the laser would exclude any mechanical vibrations of the optics and pump power fluctuations. Then, laser noise is limited by the effect of quantum noise. In simple cases, the timing noise spectral power density of mode-locked lasers as an effect of quantum noise scales with small signal gain, the square of the pulse duration and inversely with the intracavity pulse energy and round-trip time [19]. This explains why mode-locked solid-state lasers have a great potential to exhibit low phase noise. They usually operate with low cavity losses and thus have a small saturated gain value. Additionally the rather high obtainable power levels lead to a relatively large intracavity pulse energy. For edge-emitting external cavity semiconductor lasers the situation is typically different: They suffer from high cavity losses and thus have a high saturated gain. Additionally, they have strong power limitations keeping the intracavity pulse energy low. Thus their quantum noise induced phase noise is relatively high compared to mode-locked solid-state lasers. On the other hand, the cavity setup is typically more rugged so that mirror vibrations play less of a role. The third candidate for PGLs with high repetition rate, the mode-locked fiber ring laser profits from its long cavity length, leading to a long round-trip time. This can more than compensate for the relatively high cavity losses. However, special care has to be taken to suppress supermode noise due to harmonic mode locking 48.

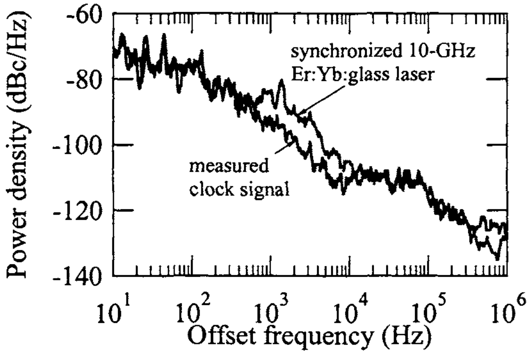

Fig. 5 Phase noise power spectral density for clock signal and synchronized Er:Yb:glass laser measured with von der Linde method. Apart from a narrow window around 1 kHz the laser noise equals the measured clock noise which is mainly limited by the local oscillator in the microwave spectrum analyzer. The integrated (10 Hz – 1 MHz) phase noise yields an rms timing jitter of below 80 fs.

The repetition rate of the PGL's pulses for a 10-Gb/s connection is defined by the applied standard. For example, SONET (Synchronous Optical NET) STS-192 requires a repetition rate of 9.95328 GHz. However, in practice there are a number of different data rates possible. If forward error correction (FEC) is applied, the required pulse repetition rate has to be adjusted to 10.667 GHz, or even higher with more sophisticated FEC coding. A pulse source with continuously tunable repetition rate increases the flexibility of a network and allows for later upgrades to different transmission standards. The complex setup of a harmonically mode-locked fiber ring laser requires readjustment of several other parameters when adjusting the repetition rate. This is significantly simpler for hybrid mode-locked semiconductor lasers.

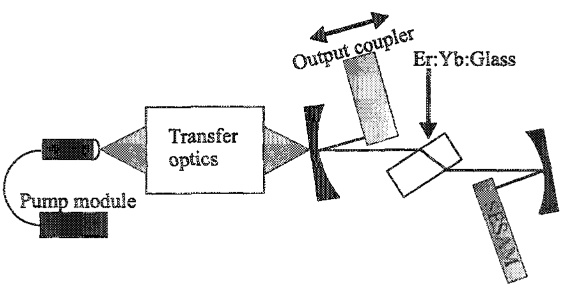

Fig. 6 Setup of the repetition rate tunable four mirror 10-GHz Er:Yb:glass laser.

We refined the three-mirror-cavity setup (Fig. 1) by using a four-mirror-design (Fig. 6). By the addition of a flat mirror the cavity can be arranged in such a way that a large laser mode is obtained on the flat output coupler. This allows to tune the repetition rate simply by moving this end mirror along the beam axis. Due to the large laser mode on the flat output coupler, the beam divergence is very small. Thus the stability region with respect to the position of the output coupler is very wide, and movement of it only weakly affects the mode sizes in the gain medium and on the saturable absorber. Therefore, the main laser parameters (pulse duration, output power and optical bandwidth) hardly change, and the tuning range is mainly limited by geometric factors (i.e. achievable travel range). This setup significantly reduces the dependence of the laser mode size in the gain, on the SESAM and in the output beam on repetition rate, thus avoiding problems like changing output power, beam quality, pulse duration, or fiber coupling efficiency. With this cavity setup, we can vary the pulse repetition rate between 8.8 GHz to 13.3 GHz with negligible variation of the main pulse parameters (Fig. 7) [49]. This tuning range allows the laser to be used for all the different RZ transmission standards at 10 Gb/s as well as a multi-wavelength source for the ITU channel spacing of 12.5 GHz (see Section 4.2).

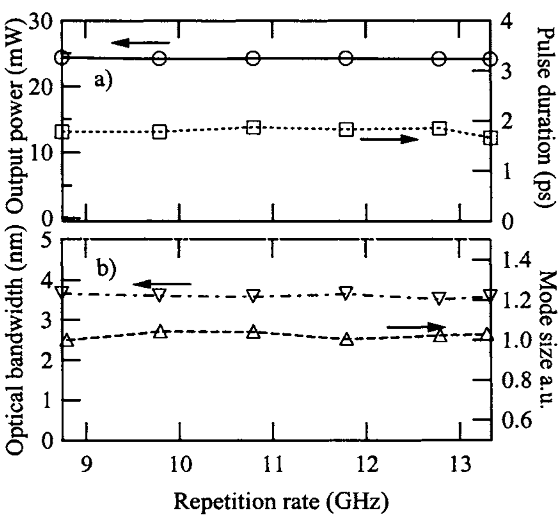

Fig. 7 a) Output power (solid) and pulse duration (dotted) and b) optical bandwidth (dashed-dotted) and relative output beam size (dashed) as a function of repetition rate. The main pulse parameters remain essentially unchanged during tuning the repetition rate from 8.8 to 13.3 GHz.

4.1.2. 40-GHz pulse generating lasers

We have also developed an Er:Yb:glass laser directly generating a pulse train with 40-GHz repetition rate [50]. The laser is based on the same principles and the same cavity setup as shown in Fig. 1. Also the pulse parameters are similar to the 10-GHz laser (18-mW average output power, 4.3-ps pulses). Due to space constraints in the extremely short cavity, we did not prove wavelength or pulse repetition rate tunability yet. For space reasons, for repetition rates higher than 10 GHz, we used 40% thinner Er:Yb:glass Brewster gain elements. Due to the somewhat decreased pump absorption and the inferior mirror quality of the more strongly curved mirrors, the overall efficiency decreased slightly at these repetition rates. The reduced interaction length of pump and gain could theoretically be compensated for by the use of adjusted Yb and Er concentrations of the gain element.

4.2. Wavelength domain

In the wavelength domain, fundamental-mode-locked lasers generate a stable comb-shaped optical spectrum (Fig. 3b), where the spacing of the individual longitudinal modes exactly equals the pulse repetition rate and shows a high optical signal-to-noise ratio (OSNR). Therefore, pulse-generating lasers are intrinsically wavelength-stable multi-channel sources which can be used as comb-generating lasers in dense wavelength-division-multiplexing (DWDM) [8,9]. 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 is automatically locked to the ITU grid. The distinct channels of the laser can be separated with appropriate means (e.g. an arrayed wave guide grating [51]), individually modulated and recombined to launch into the network [52]. Compared to the classic DWDM approach with one fixed-wavelength-laser per channel, the comb-generating laser approach brings many benefits to the system, such as decreased number of components (i.e. only one set of driver electronics and one wavelength locker are required), smaller inventory, space and power requirements, etc.

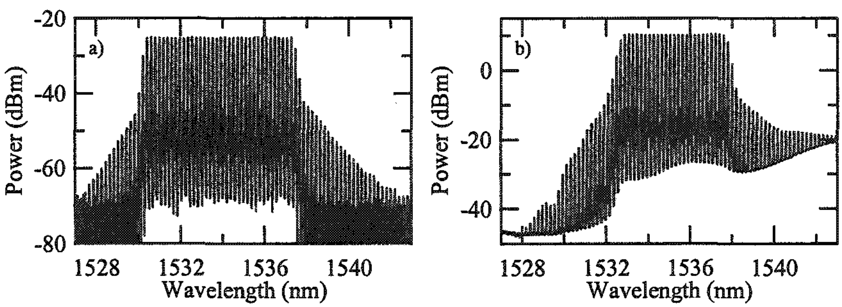

Fig.8 Optical spectrum from 25-GHz a) laser flattened with DGE and b) flattened with DGE and amplified with an EDFA.

As current channel spacing standards are 25 GHz, 50 GHz, 100 GHz, or higher (International Telecommunication Union, ITU), we developed a 25 GHz and a 50 GHz version of the Er:Yb:glass laser [53,54]. Fig. 1 still holds for the cavity designs. The overall cavity length is then about 6 mm and 3 mm respectively. Also the output parameters are very similar to the 10-GHz and 40-GHz lasers: several mW average power, about 2-ps pulse duration, 30-dB contrast ratio, and a 2-3 nm of spectral FWHM. We could tune the wavelength of the 25-GHz laser in the range of 1528 – 1561 nm. 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. 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 (four times more for the 50-GHz laser), which is well below the tolerance of the ITU channels and typical bandwidths of DFB lasers. The reason for this small change in repetition rate is that the carrier frequency is several orders of magnitude higher than the repetition rate itself. Therefore, a sub-wavelength change in cavity length has only a minimum impact on the channel spacing.

For a DWDM application each channel (longitudinal mode) should have the same power rather than the Gaussian like spectrum of a typical mode-locked laser. Therefore, we combined the 25-GHz laser with a dynamic gain equalizer (DGE) (Silicon Light Machines, Model:SLM2200). The DGE allows setting the attenuation of each channel individually and in real time, controlled by a computer. Fig. 8a shows the optical spectrum of the laser (without etalon) in conjunction with the DGE. A fraction of the output is detected and checked for flatness. This gives an error signal which is fed back to the DGE. Using the maximum dynamic range of the DGE (17 dB), we could get up 32 channels with a flatness of better than 0.4 dB. In order to increase the power per channel, we added an EDFA to the system (after the DGE). The gain narrowing reduced the number of channels to 25, however each carrying 10 dBm average power, and an OSNR exceeding 35 dB (Fig. 8b). No additional filters have been used to suppress the amplified spontaneous emission of the EDFA. The system is very stable, as the original laser spectrum is stable and adaptive flattening is applied in addition.

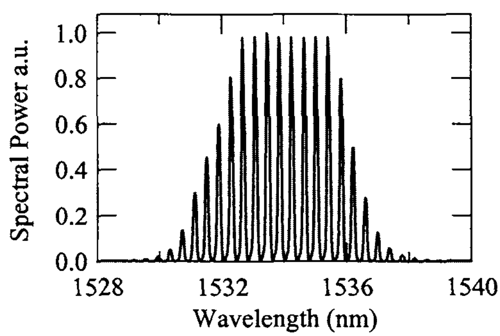

Fig.9 Optical spectrum from 50-GHz laser flattened with DGE.

Increasing the pulse repetition rate leads to a wider channel spacing. This relaxes the demands on the filter characteristics of the channel add/drop nodes, and it allows for higher channel capacities. Therefore, we have developed a 50-GHz Er:Yb:glass laser [54]. For locking the longitudinal modes of this 50-GHz comb to the ITU grid, we used a simple feedback loop consisting of a wavelength locker from JDS Uniphase, a simple integrating circuit, and a piezo below the SESAM to tune the cavity length. Fig. 9 shows the optical spectrum of the multi wavelength source, locked to the ITU grid. Here, for flattening we used a somewhat simpler DGE (ZettaManager 12-band from ZettaLight) with less maximum dynamic range (10 dB) and a coarser channel spacing. Therefore, only up to 10 channels with a flatness <1 dB have been generated. The power in each of the equalized modes is –25 dBm. The measured optical signal-to-noise ratio (OSNR) was 65 dB, probably limited by the spectrometer.

Keeping in mind the simplicity of this approach, its potential for DWDM system applications becomes clear. An additional stage for super-continuum generation can even increase the number of obtained channels substantially [52]. The super-continuum generation would benefit from the spectral purity and stability of the presented laser. In first super-continuum generation experiments carried out at 10 GHz we obtained a stable smooth spectrum ranging from 1450 nm to 1650 nm. For that the pulse train from the laser was amplified in an EDFA and launched into a highly nonlinear fiber, generating a huge number of additional longitudinal modes, still exactly spaced by the repetition rate of the seed laser.

5. Conclusion

We have presented various novel multi-GHz sources, all based on diode-pumped, passively fundamental mode-locked Er:Yb:glass lasers. The application of a semiconductor saturable absorber mirror in combination with optimized cavity designs allowed progression in performance regimes where these lasers enable and/or improve new approaches for telecom applications. The combination of passive mode locking of a solid-state laser with active synchronization leads to outstanding pulse properties in a simple and cheap setup. Main characteristics are high contrast ratio, short pulses, clean spectrum with high signal to noise ratio, and low timing jitter. The main pulse parameters can be varied in a wide range. I.e. turn key tuning of the wavelength throughout the C-band and the repetition rate covering all the different RZ transmission standards at 10 Gb/s has been presented. Pulse durations between 1 ps and 19 ps and pulse repetition rates of 10, 25, 40, and 50 GHz enable OTDM and DWDM applications.

For future development, repetition rates beyond 80 and 100 GHz seem to be appealing for higher bit rates or larger channel spacings. Possible limiting factors are the extremely small cavity dimensions and Q-switching instabilities. Also introduction of a tuning element in the 40 and 50-GHz lasers is a challenge. Further, we believe that with improved mechanical design and phase-locked-loop electronics, the rms timing titter can still be significantly reduced.

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