ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

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International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 1056246 · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296201

FIBER BASED OPTICAL FREQUENCY COMB – TECHNICAL CHALLENGE FOR SPACE APPLICATIONS

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ABSTRACT

In this paper we present the basic working principle of a fiber based optical frequency comb, the advantages for using this technology for space applications and the limitations and technical challenges arising from environmental conditions in space. OHB System is investigating this technology and the possible usage of such system since 2006. In this paper we present the development made in the recent years and the lessons learnt bringing such a system towards space operation.

It has been pointed out that the limiting element in performance in terms of phase noise and linewidth transfer is the laser oscillator itself. First of all, an oscillator technology must be selected fulfilling the performance requirements before thinking about space engineering. Basically three different types of mode locking mechanism for femtosecond fiber lasers are considered herein, an absorber based mode-locking (SAM), a nonlinear polarization rotation (NLPR) mode-locking and nonlinear amplifier loop mirror (NALM) mode locking based laser. For all three technologies advantages and disadvantages in terms of noise performance and possible use in space applications arise. In this paper the results of different test (radiation and thermal-vacuum test) carried out for a NLPR and a SAM mode-locked laser are presented.

I. INTRODUCTION

In an optical frequency comb a laser oscillator, in the case here a fiber based laser, generates ultra-short light pulses with pulse durations in the femto-second regime. These pulses have a certain pulse repetition rate (f_r) which is controlled by different actuators implemented within the oscillator. In the frequency domain, these pulses can be identified as distinct Dirac pulses appearing at the harmonic frequencies of the repetition rate. In addition these harmonic frequencies are shifted by the so called carrier envelope offset frequency (f_0) from the zero frequency. In Fig. 1 a schematic view of the different frequencies resulting from the Fourier transform of the pulses in time domain is given. The repetition rate (fr) is defined by the optical path length of the laser resonator and is inverse proportional to the time difference between two adjacent pulses. The carrier envelope offset frequency has its origin in the time varying phase shift between the maximum of the electrical field within the envelope with respect to the maximum of the envelope itself. The origin of the CEO frequency lies in the mismatch of the group and phase velocity in every dispersive medium. This frequency is more complex to detect and to stabilize, which is shown later in section II.B.
To use the frequency comb for measurement applications both frequencies have to be stabilized to a fixed reference.

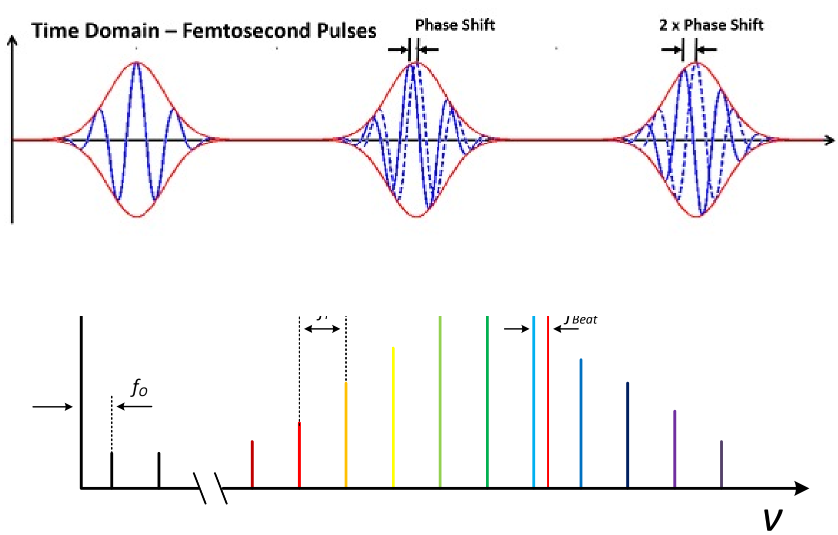


Fig. 1: Top: Pulse train in time domain illustrating the envelope (red) of the electrical field (blue). Bottom: Illustration of the different frequencies obtained by Fourier transformation of the pulse train in time domain.

An optical frequency comb therefore works like a frequency gear, transforming the optical light frequency of hundreds of tera-hertz into mega- or giga-hertz frequencies [1, 2].
Laser light with unknown frequency is locked to e.g. one tooth of the OFC and by measuring the resulting beat frequency (f_{Beat}) and subsequent calculations with the stabilized and known tooth-frequency of the OFC the unknown frequency can be calculated. So, the optical frequency comb is nothing else than a highly accurate optical ruler opening the possibility to measure the wavelength of unknown light with accuracies better than 1 Hz. In fact if the laser is locked onto an optical atomic clock (OAC) accuracies in in the mHz regime are possible, which is sufficient to be used as high precise GNSS time base. Here the relative stability is the same as for the optical transition of the OAC.

II. OPTICAL FREQUENCY COMB SETUP

The challenge in an OFC setup is first to generate high purity pulses by the laser oscillator because the linewidth of the frequency modes and therefore the overall accuracy is limited by the pulse quality in terms of pulse duration and spectral bandwidth. The second challenge arise by the detection of the offset frequency (f_0). This frequency is a synthetic frequency which can be detected by the use of a special setup, a so called f-2f-interfermoeter which is explained in more detail in section II.B. The quality in terms of phase noise and signal-to-noise ratio (SNR) of the generated offset frequency depends highly on the noise generated by the laser oscillator.

Fig. 2 illustrates a fully stabilized OFC setup in which the laser oscillator generates the ultra-short pulses which are amplified afterwards by an erbium doped fiber amplifier (EDFA). Subsequent to the EDFA a pulse compression unit (free space or fiber based) is necessary to compress the light pulses further to enable the spectral broadening within a highly nonlinear fiber (HNF). The spectrum of the laser is fed to the f-2f-interferometer in which the synthetic frequency f_0 is detected. The frequencies f_{Rep} and f_0 are fed to a control electronic which generates the control signal for the actuators to stabilize the frequencies to an external reference.

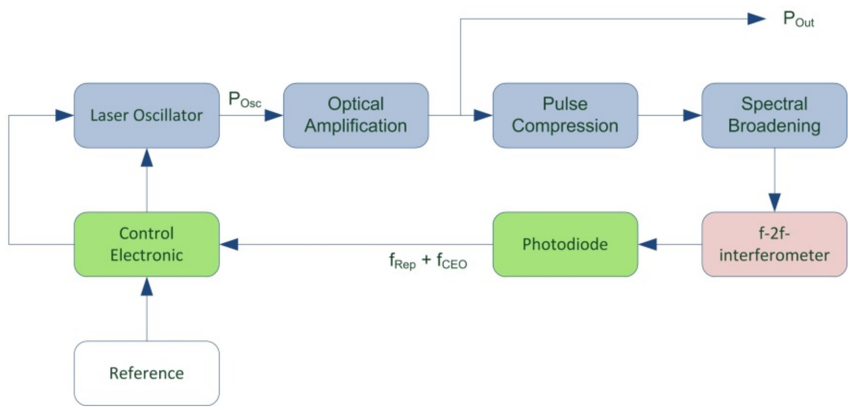


Fig. 2: Block diagram of a fully stabilized optical frequency comb.

A. Laser Oscillator

In order to generate ultra-short laser pulses in the femtosecond regime, a technique called passive mode-locking is most commonly used. Under the terminology passive mode-locking the Kerr-lens mode-locking, the nonlinear polarization rotation mode-locking (NLPR), the saturable absorber mirror (SAM) mode-locking and the nonlinear amplifying loop mirror (NALM) mode-locking are encompassed.

Free-beam systems like the well-known Titanium-Sapphire laser use Kerr-lens mode-locking. Thereby the combination of a non-linear Kerr-medium and an aperture works as an artificial absorber to focus only the high intense pulse center [3]. Concerning the space application point of view, a Ti:Sa-laser has a low efficiency and a high sensitivity to environmental conditions such as vibrations, temperature and pressure in comparison to a fiber based laser. Therefore this laser type is not taken into account in this paper.
Fiber based laser system have advantages in terms of stability, vibration sensitivity and cost, here three different types of mode-locking techniques are presented including their advantages and disadvantages.

A. 1st Generation - Non-Linear Polarization Rotation (NLPR) based Oscillator

The first laser system which was tested at OHB in 2006 was a NLPR based laser oscillator with a central wavelength of 1550 nm, an optical output power of 50 mW, a spectral width of 40 nm, a pulse width in time domain of 100 fs (Gaußian pulse shape) and a pulse repetition rate of 100 MHz. This laser type was the first type under investigation at OHB and is therefore named as the 1st generation laser oscillator.

Nonlinear polarization rotation (NLPR) mode-locking relies on the intensity dependent rotation of an elliptical polarized light in a length of optical fiber [4, 5, 6, 7]. The elliptic polarized light can be resolved into right- and left-hand circular polarization components of different intensities. These two components accumulate different nonlinear phase shifts while traveling through the single-mode amplifier-fiber because of the intensity dependence of the refractive index. The light passes through the optical fiber in which the peak of the pulse with high intensities rotates more than the low intense pulse wings. The low intense pulse wings are filtered out by wave plates and a polarizer.

The rotation of the high intense pulse center in comparison to the low intense pulse wings is described by [8]:

$$\Delta\phi = \gamma \cdot \frac{P_0}{3 \cdot \cos(2 \cdot \Theta)} \tag{1}$$

Where P_0 is the pulse peak power launched into the fiber, γ is the nonlinear coefficient of the fiber according [9], L is the length of the fiber and Θ is the angle between one fiber axis and the linear polarized light.

An optical pulse traveling around a cavity formed by an optical fiber and some free space paths including the two polarization states is illustrated in the left hand side of Fig. 3.

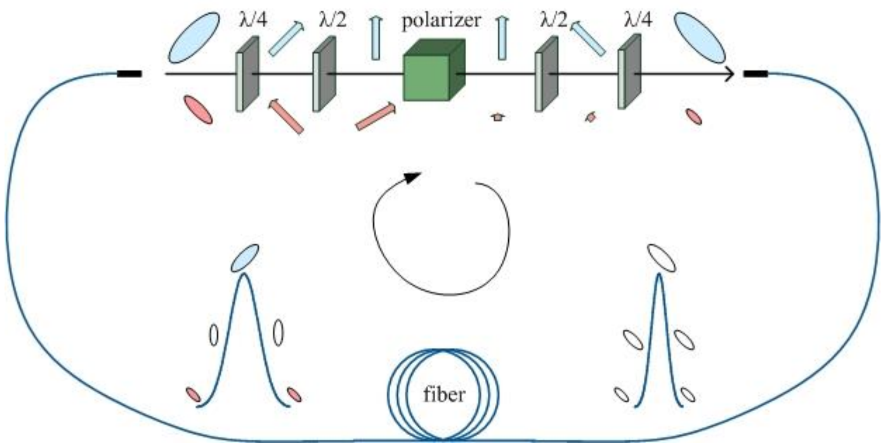


Fig. 3: Basic principle of the nonlinear polarization rotation mode-locking. The high intense pulse center (light blue) is rotates in the fiber more than the low intense pulse wings (light red). The low intense pulse wings with a certain polarization are filtered out by waveplates and a polarizing element.

The advantages and disadvantages of the NLPR based laser are given in Tab. 1. The laser is able to generate laser pulses with a high repetition rate due the possible short fiber, in addition also the generated carrier envelope offset frequency (f_0) shows low phase noise with respect to the SAM based laser oscillator. Nevertheless the technological disadvantages such as vibration sensitivity, complex control and sensitivity to radiation and temperature make this laser poorly attractive for space missions. The negative effects were discovered during the environmental test series of this laser, see also section III.A.

Tab. 1: Advantages and disadvantages of a NLPR based laser oscillator.

Advantages (+++)	Disadvantages (- - -)
Well known design	Actuators such as motors necessary to rotate wave-plates
High repetition rates due to short fibers possible	Free space paths make system sensitive to vibrations
High output power possible	Complex design for free space path to compensate for temperatures and deformation
Low phase noise for the generated offset frequency f_0	Actuators must be adapted during operation to maintain mode-locking state
	Position of actuators must be stored, complex control needed
	Pressure changes the refractive index (free space paths) so different performances are obtained for ambient and vacuum.
	Strong performance degradation due to radiation effects (TID)
	Polarization maintaining (PM) setup hard to establish

B. 2^{nd} Generation - Saturable Absorber Mirror (SAM) based Oscillator

First investigations concerning a SAM based laser where carried out at OHB in 2010, more focus on this laser oscillator technology was given in 2013 after the drawbacks of the NLPR laser have been fully identified. The first tested laser was a commercial laser based on Yb-doped fiber with a central wavelength of 1030 nm, an optical output power of 10 mW a pulse width of 6 ps ($sech^2$ pulse shape) and a pule repetition rate of 21 MHz.
In the beginning of 2012 a second SAM based laser oscillator was tested at OHB, this unit has received special modifications and has a central wavelength of 1550 nm with pulse durations around 200 fs. So the second laser type is more comparable in performance parameters with the NLPR laser oscillator from the 1^{st} generation.

For the SAM based laser a saturable absorber inside the resonator modulates the losses inside the laser cavity [10] and acts as mode-locking element. The saturable absorption is a material property due to the fact that in the absorber layer of the SAM atoms in the ground state are excited into a higher energy state by incident photons. If the rate of photons is high enough, the ground state depletes and thereby the absorption saturates [11, 12].
After formation of a stable laser pulse (steady-state) the SAM efficiently absorbs residual laser light and therefore stabilizes the circulating laser pulse. At the beginning the pulse is organised out of the noise generated by the amplified spontaneous emission (ASE).

A laser oscillator based on SAM mode-locking shown in Fig. 4, in the case here a linear architecture is shown. The laser oscillator is formed by the fiber coupled mirror and the SAM, acting as intensity dependent mirror. Light is fed in and out of the laser cavity by the help of a wavelength division multiplexer (WDM) and an optical isolator respectively.

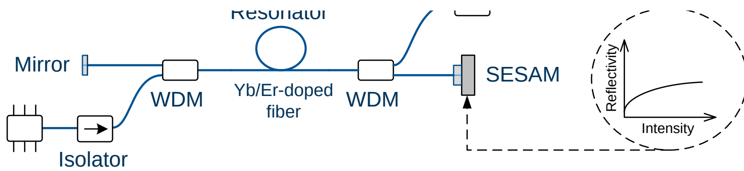


Fig. 4: Schematic illustration of a SAM based laser oscillator. The SAM acts as mode-locking element in that sense that only high intense light is reflected back.

The advantages and disadvantages of the SAM based laser oscillator are given in Tab. 2. The main advantage for the SAM based laser is the possibility to build a nearly all-in-fiber laser oscillator beside the small path before the SAM element in the case of an external semiconductor based SAM. The mode-locking control is fully passive and self-starting, so no actuators or complex control mechanisms are necessary. The disadvantage of the oscillator is the lower quality of the offset frequency (f_0) due to high internal losses and imperfect matched GVD resulting to a net dispersion non equal to zero. In a perfect matched oscillator, the performance is only limited by the relaxation time of the used SAM element.

Tab. 2: Advantages and disadvantages of a SAM based laser oscillator.

Advantages (+++)	Disadvantages (- - -)
All in fiber setup	Low output power (~1-2mW)
Can be built with Yb/Er-doped fibers	High losses inside cavity
More robust against vibrations than NLPR	CEO frequency (f_0) showed low performance (low SNR of ~33dB and broad spectral width of 300kHz)
Easy of control, self-starting possibility	Careful design necessary to compensate GVD and SPM to obtain low noise laser oscillator
Semiconductor based SAM tested up to 90 krad without degeneration.	SAM limits the performance of the generated frequencies specially the CEO frequency f_0

C. 3^{rd} Generation - Nonlinear Amplifying Loop Mirror (NALM) based Oscillator

The later fiber-laser technology under investigation at OHB is the so called nonlinear amplifying loop mirror (NALM) laser oscillator. In this laser, the NALM (illustrated by the loop on the right side of Fig. 5) work as a artificial saturable absorber [17, 18]. Light which is coupled in from the main oscillator on port 1 into the NALM propagates clockwise (cw, port 3) and counterclockwise (ccw, port 4) through the NALM ring. When the oscillator enters the pulsed operation, the asymmetric amplification results in a non-linear phase shift for pulses traveling in ccw-direction. When this phase shift reaches the value of π, the power is transmitted to port 2

and not anymore to port1 for which the pulsed signal can pass the isolator without losses. From the oscillator section a small part is coupled out which is afterwards amplified and compressed (not shown in Fig. 5).
The advantages and disadvantages of the NALM based laser oscillator are given in Tab. 3. The simulation of the laser oscillator in combination with the NALM is a challenge task, in addition the behaviour of the laser is not known when the coupling ratio of the central coupler or the attenuation in the fiber of the NALM loop is changed. Changes herein could result from radiation effects or thermal sensitivity of the used components.

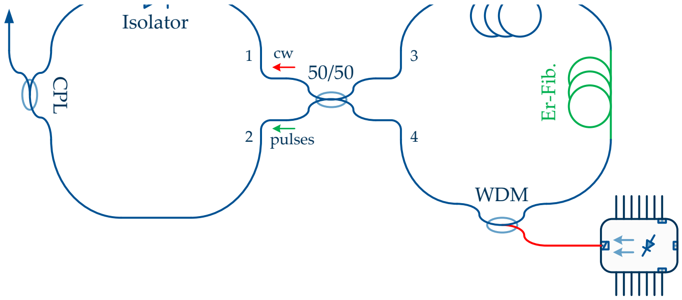


Fig. 5: Nonlinear Amplifying Loop Mirror (NALM) based oscillator from [17].

Tab. 3: Advantages and disadvantages of a NALM based laser oscillator.

Advantages (+++)	Disadvantages (- - -)
All in fiber Setup	Low output power (~1-2mW)
Can be built with Yb/Er-doped fibers	Complex to simulate
More robust against vibrations than NLPR	No Self Starting: Often additional components are required such as phase shifter, EOM or vibrations/ mechanical shocks
Due to fast Kerr-lock mechanism, broad band spectral operation and dispersion managed cavity design	Effects due to changes in coupling ratio unknown, further investigations necessary

B. f-2f-Interferometer

As given in section I, a special interferometer is necessary to detect the CEO frequency. In frequency domain the CEO frequency can be calculated from the CEO phase shift and with the repetitionrate f_R to:

$$f_0 = \frac{\Delta\varphi_0}{2\pi} \times f_R = \frac{\lambda}{2\pi} \cdot \left(1 - \frac{v_g}{v_p}\right) \quad (2)$$

The idea behind the detection of the CEO frequency is as following: The red part of the light (around 1µm) is frequency doubled in an Second-harmonic generation element (SHG). This newly generated frequency contains *2n* times the repetitionrate and two times the CEO frequency. This frequency is superimposed with the blue part (around 2µm) of the spectrum. The superimposed output light has a beat frequency of exactly the difference and sum frequency of the two superimposed beams.
The detector acts as lowpass filter eliminating the sum frequency terms, hence the frequency seen on the photo detector is given by:

$$f_{pd} = 2f(n) - f(2n) = (2 \cdot n \cdot f_R + 2 \cdot f_0) - (2n \cdot f_R + f_0) = f_0 \quad (3)$$

For which the mirror frequencies between fR and f0 are not taken into account, these parts must be filtered in the RF domain. Behind the f-2f-interferometer and a single detector both frequencies (f_R and f_0) can be detected.

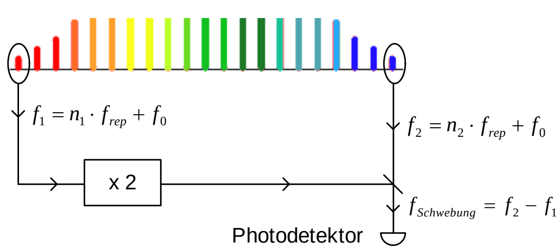


Fig. 6: Basic idea to detect the CEO frequency. The longer wavelength part (~2µ) is frequency doubled in a SHG crystal and then superimposed with the fundamental light (1µ).

III. MEASUREMENT RESULTS

A. Environmental Tests of Laser Oscillators

For the NLPR laser a thermal test was performed to identify the sensitivity of the repetition rate to temperature changes, which is later-on important for the design of a thermal control of the oscillator. It is assumed that the behaviour of an all-in-fiber-setup shows identical behaviour. In principal two effects changing the repetition rate were identified:

- Refractive index change of the optical fiber n = f(T)
- Length change of the optical fiber $l_{Fib} = f(T)$

The variation in repetition frequency due to temperature is given in Fig. 7, the sensitivity is computed to -923 Hz/K within the tested temperature range. Because of the fact that the frequency control actuators have only a limited range (approx. 150Hz) a thermal control of the laser oscillator is necessary to ensure long term operation. This holds also true for laboratory applications.

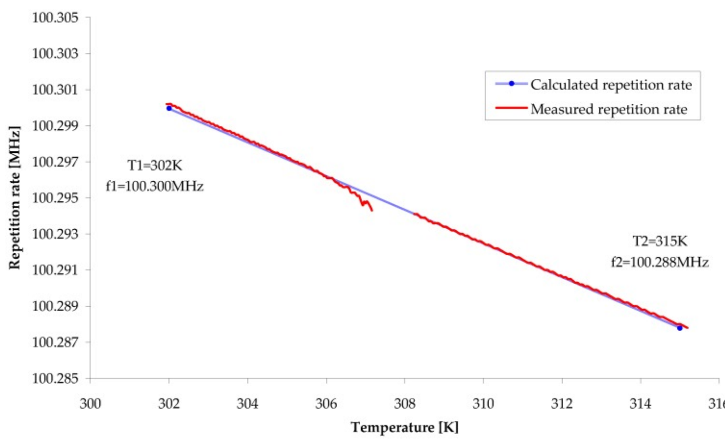


Fig. 7: Measured repetition rate (f_R) as function of temperature (red) and theoretical calculated curve.

$$\frac{\Delta f}{\Delta T} = -923\frac{Hz}{K} \pm \frac{1Hz}{K} \tag{4}$$

For the same NLPR laser also a gamma radiation test with a Co-60 source was carried out to investigate the eventual present degradation of the laser setup. For this measurement the optical output power (see Fig. 8 on left) and the optical output spectrum (see Fig. 8 on right) are measured online during the test. The optical output power decreased and after approx. 28.8 krad the laser lost its mode-lock state and started to search for a new one. Since the optical output power had decreased, a new mode-lock state with the parameters set in the control software has not been found. In the optical output spectrum (see Fig. 8 on the right) a growing of a cw-peak at 1537 nm was observable yielding to a less broad output spectrum and a longer time duration of the generated pulses.

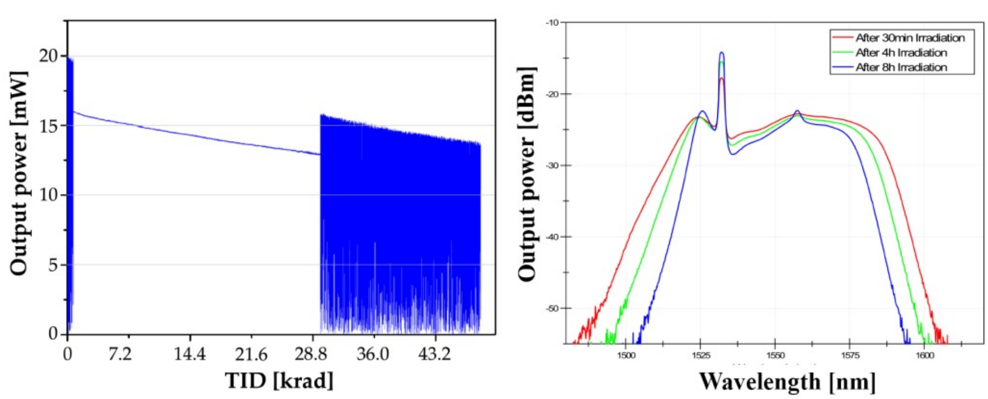


Fig. 8: Left: Optical output power of the NLPR Er-fiber laser during gamma radiation test. Right: Optical output spectrum showing a large cw-peak which increases with total dose.

The same test was carried out for the SAM based Yb-fiber laser, the results are illustrated in Fig. 9 for the optical output power on the left and on the right for the change in optical outputs spectrum, respectively. The

Yb-fiber laser showed moderate power losses of 0.1 %/krad for a total dose of more than 156 krad. In comparison to the Er-based NLPR, the Yb baser laser is by a factor of eight less sensitive to gamma radiation.

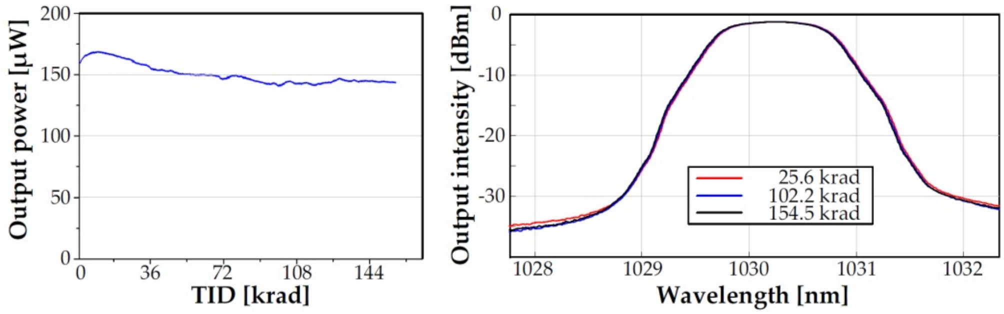


Fig. 9: Left: Optical output power of the SESAM based Yb-fiber laser during gamma radiation test. Right: Optical output spectrum at different TID levels.

In parallel to the radiation test series also the impact of gamma radiation to Er- and Yb-doped fibers was investigated. For this two different setups where established, a simple amplifier setup without seeder signals for which only the ASE signal was measured and another amplifier setup which was seeded with femto-second laser pulses. The results are summarized in Tab. 4. The Er-doped fiber in the amplifier without seeding pulses showed the worst performance, whereas the Yb-fiber was better but also this fiber was affected by the gamma radiation. The results are comparable with the data obtained in [14, 15].

Tab. 4: Radiation test results for different rare-earth doped amplifier fibers.

ASE Measurement	**Total Dose [krad]**	**Degeneration [%/krad]**
Er-doped fiber	14.5	2.15
Yb-doped fiber	10.8	0.62
ER-doped rad-hard fiber	57.6	0.20
Amplifier Measurement		
Er-doped fiber	81.0	0.72
Yb-doped fiber	48.1	0.23
ER-doped rad-hard fiber	81.8	0.15

When the amplifiers are seeded with the femto-second pulses, the degradation is much lower for the non-rad-hard fibres. The origin lies in the photo-bleaching effect, incident light, especially with high pulse peak power, works against the creation of colour centres in the fibers which increase the losses inside [15]. Nevertheless for a final defined laser technology, a detailed test for each component and different fiber types must be done.

B. Characterization Measurements

In this section some important measurements for the SAM based laser oscillator (2nd generation), optically locked to a HeNe reference laser, are given. The measurements shall give some hints which parameters are important, especially for the design of the control electronics.

In Fig. 10 on the left side an open-loop power transfer function of the laser oscillator is given. The laser has multiple actuators to stabilize the repetition rate for example. As can be seen, stabilising the laser over its pump power is limited to a bandwidth of 9.7 kHz. The limitation arises from the long life time of the erbium ions in the range of 10 ms and the laser cavity dynamics. When thinking on a free-running linewidth of the CEO frequency of 300 kHz for example, it is clear that single pump power control with a bandwidth of 9.7 kHz cannot be used to counteract deviations with 300 kHz, it is simply too slow. By correct controller tuning this bandwidth can be increased up to 900 kHz, but this specialized expertise and hardware. But in contrast to the low bandwidth of the pump power actuator, the stabilization over the intra-cavity EOM has a gain transfer function as given in Fig. 10 by the blue curve. Therefrom a bandwidth of 625 kHz can be obtained which could also be used for phase-locking the CEO frequency.

Another interesting measurement which was taken from the 2nd generation SAM laser oscillator is related to the linewidth of the CEO frequency as function of the relative intensity noise (RIN) of the pump power. This measurement is shown in Fig. 10 on the right side and illustrates that a RIN value of approx. -125 dBc/Hz is necessary to do not broaden the CEO frequency by the pump laser diode. For each new laser oscillator this measurement must be repeated. Based on this result also the maximum allowed noise contribution of the pump laser assembly (laser and current control electronic) is defined.

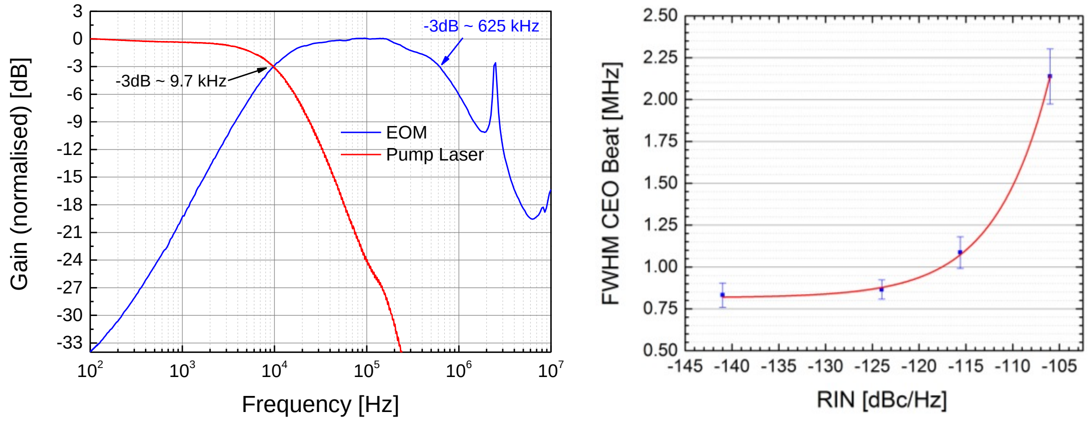


Fig. 10: Left: Transfer function measurements for the stabilization actuators (pump diode and integrated EOM) [18]. Right: CEO linewidth (FWHM) as function of the relative intensity noise (RIN) of the pump diode.

C. Performance Measurements

With the SAM based OFC different performance measurements were made, here a measurement is presented for which the comb system was used to read out a 633 nm HeNe transfer laser which was locked to a ring-laser located in Wettzell, Bavaria. A special interface unit was designed by the measurement team in Wettzell to convert the 1560 nm of the comb to the target wavelength of 633 nm [20]. A comb line (n * fR) was locked to a HeNe laser with the intra-cavity EOM as actuator. By appropriate design of the control electronics an overall bandwidth of approx. 1 MHz was achieved.
In Fig. 11 on the left side the relative beat frequency of the optical lock is illustrated, the servo bumps of the CEO lock and of the optical lock can be identified clearly. An SNR of approx. 30dB was achieved when the lock was established. On the right side of Fig. 11 the frequency deviation over 10,000 seconds is illustrated, the deviation was in the order of +/- 10 mHz in the given time interval which is considerable good for the first fully stabilized laser oscillator at OHB.

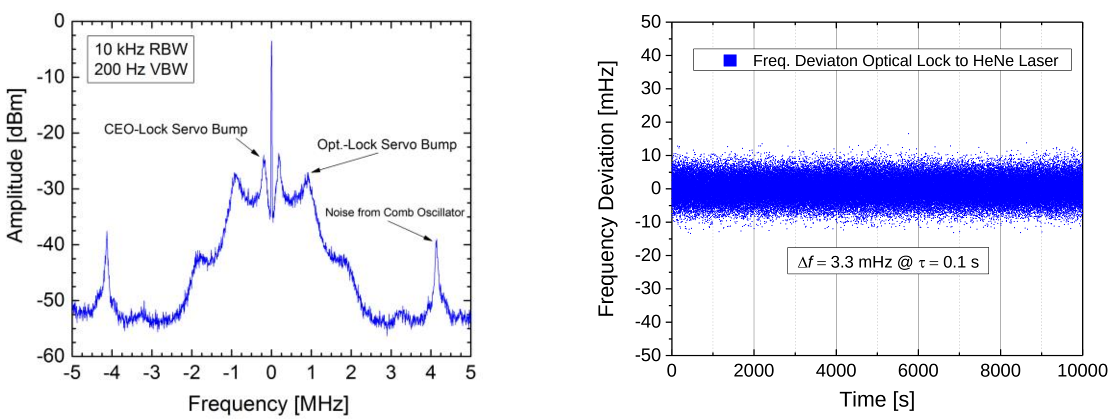


Fig. 11: Beat signal when the SAM based comb is stabilized to a HeNe laser (left) and corresponding frequency stability of optical lock (right) [20].

IV. DESIGN CHALLENGES

In this section some design challenges and considerations are given, the results are derived by tests and measurements to different laser oscillator designs and control electronic setups. The focus is given special to the laser assembly rather than to the control electronics.

- Characterization measurements:
  Time spent to a detailed system characterisation is not a waste in time, it is very important to know the system. Especially when the laser is not an in-house construction, detailed knowledge must be collected even when only a specification for a subcontractor is written. Measurements such as transfer functions and pump power sensitivity shall be done in minimum.

- Behaviour in the real environment:
  Such laser systems are mostly used in laboratory environment, but for space applications special consideration to the environment must be given. As minimum, the thermal sensitivity of the laser shall be measured, the results indicate direct if a thermal control of the laser oscillator is needed and with which accuracy. If the laser is sensitive to vibrations and shock can be tested very easily, just know with the fingers on the mechanical housing of the laser and observe the frequencies on the electrical spectrum analyser. In the best case no spikes or changes in the lock-signals shall be observed.

- Radiation effects:
  All three presented laser concepts contain different fiber-optic elements which are definitely not available as space qualified parts. Once a suitable laser technology is selected, the different parts inside the laser must be identified and analysed. We suggest to conduct a separate test for each component at least a thermal test and a gamma radiation test are necessary to prove if these components could be used for space applications. The performance parameters shall be defined before the test, also a literature inquiry is at this point helpful.

- System design:
  Especially for the fiber-optical system special care must be taken. All elements rely strongly on each other, because the propagation of ultrashort pulses is a complete other topic than for continuous light waves. The fiber lengths and the dispersions must be exactly matched to allow for example a pulse compression in the fibers or the generation of the supercontinuum. So buying all needed elements from different companies is will definitely result in a non-working system as long the interfaces are not specified exactly. And this specification is very hard to establish for non-linear systems.

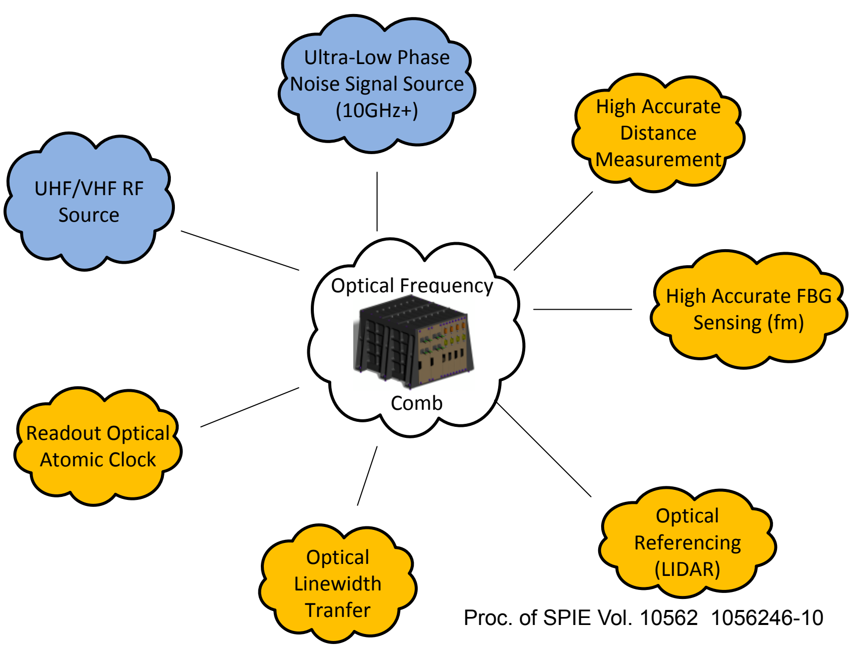
V. APPLICATIONS FOR FUTURE SPACE MISSIONS

The last section gives some application ideas for a frequency comb in space applications. Optical systems could benefit from the OFC which could be used for very accurate absolute distance measurements in deep space formation flights, laser stabilization systems for future LIDAR applications for climate gas monitoring and for the transfer between optical frequencies downwards radio frequencies as it is required for optical atomic clocks.

In addition high accurate interrogation for fiber-Bragg grating (FBG) sensors in the sub femto-meter regime is possible. A second interesting area are radio-frequency systems which would benefit from a frequency comb such for the generation of ultra-low phase noise signals at 10GHz and the generation of other carrier signals up to 40 GHz. Each comb line can be seen as a separate carrier frequency, phase coherent and available all at the same time, the upper limit in frequency is only defined by the used photodetector

As small image illustrating the possible applications is given in Fig. 12, where the yellow color indicates possible optical applications, the blue color indicate applications in the RF domain.

Fig. 12: Illustration of the possible application fields of an optical frequency comb.



VI. ACKNOWLEDGMENTS

The authors want to thank the German Aerospace Agency for co-funding the different researches (50QT0901, 50QT1001, 50RM1222) related to the different fiber laser technologies. The environmental tests of the NLPR laser and the SAM laser where funded by the European Space Agency under the contract 20071/06/NL/PM.

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