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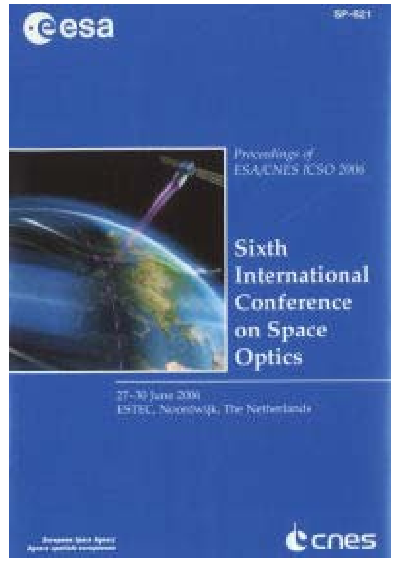

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ALL-FIBER-COUPLED, MASTER OSCILLATOR FIBER POWER AMPLIFIER BASED LASER ASSEMBLY FOR THE LISA GRAVITATIONAL WAVE DETECTOR

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ABSTRACT

We review possible alternatives for the realization of the LISA laser assembly against the requirements and present a concept for a tailored master oscillator fiber power amplifier solution. An all-solid-state, all-fiber coupled approach with a Nd:YAG NPRO seed appears particularly attractive due to the possibility to combine excellent spectral properties and high output powers with superior environmental robustness.

1. INTRODUCTION

The joint ESA/NASA mission LISA (Laser Interferometer Space Antenna) aims at detecting gravitational waves from astrophysical objects and events in the frequency range 30 µHz to 1 Hz. It will be implemented in a constellation of three identical spacecraft at the corners of an equilateral triangle with a 5 million kilometer arm length, which is trailing earth in a heliocentric orbit. Each spacecraft carries a payload with two free-falling "proof masses" defining the end points of the individual arms. The passage of a gravitational wave will cause minute changes in the distance between the two proof masses of each arm, which are observed by heterodyne laser interferometry, that mutually links the three spacecraft in an active transponder scheme.

The precision required for the detection of proof mass displacements is given in terms of the so-called strain sensitivity $h = 2\,\delta L/L$, for which a noise level below 3.2×10^{-19} at a frequency of 1 mHz has to be provided. This requirement translates into a maximum allowable metrology noise of about $12\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at frequencies above 3 mHz. Crucial for achieving this level of accuracy is an efficient scheme for canceling laser phase noise. Therefore, excellent free-running spectral properties of the utilized laser system are a prerequisite. At the same time, a relatively high output power has to be provided to compensate for the very low transmission ratio given by the 5 million kilometer transmission path. To a certain extent, these are contradictory and thus very challenging requirements.

In science operation, the LISA constellation will be served by a total of six active laser systems, two per interferometer arm. All lasers will be synchronized – i. e. phase locked – to each other, such that one selected laser acts as the constellation master. The current baseline payload architecture foresees a total of four individual laser systems per spacecraft, where each interferometer arm is served by two laser systems in cold redundancy. Switching between these has to be provided on optical bench level in order to avoid single point failures. Delivery to the optical benches is realized with single-mode, polarization maintaining fibers.

2. REQUIREMENTS

The choice of the ideal laser system for the purpose of LISA is mainly determined by the requirements on output power and – most importantly – on frequency noise in the LISA measurement band. Additionally, the operational scheme of LISA demands for further capabilities, concerning for example tunability, frequency modulation, and redundancy.

2.1. Output Power

The actual optical power that has to be delivered by the LISA laser system is basically determined by the requirement on the signal-to-noise ratio in the inter-spacecraft distance metrology, i. e. the power in the

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received beam that is available on each of the photodiodes in the science interferometers on the payload optical benches (compare [1]). From the current noise breakdown as determined in the currently ongoing mission formulation study led by EADS Astrium, 100 pW is a reasonable order of magnitude here.

Based on this value, the power transmission can be tracked back to the fiber launcher on the corresponding optical bench of the sending spacecraft. The main source of loss in this path is the diffraction limited expansion of the laser beam between the exit aperture of the transmit telescope and the input aperture of the telescope on the receive side. An optimal transmission is obtained here if the Gaussian beam radius w_0 at the transmit aperture is adjusted such that

$$\frac{d}{2w_0} \approx 1.12 \tag{1}$$

where d is the aperture diameter. In this case, a power transmission ratio of 4.545×10^{-10} results for an arm length of 5 million kilometers and an aperture diameter of 40 cm. Further loss in components on the optical benches slightly reduces the overall transmission budget to 1.856×10^{-10}, defined as the ratio of the optical power available on each science photodiode of the receiving spacecraft in relation to the optical power emitted by the fiber launcher on the optical bench of the sending spacecraft.

Therefore, at least $\sim$ 540 mW of continuous-wave power have to be delivered by the laser system to each optical bench. As the derivation of this value does not yet account for additional loss sources such as polarization loss and misalignment, we recommend to adapt a value of 700 mW as requirement for the power delivered to the optical benches. This level has to be provided at end of mission lifetime, i. e. after about 1.5 years of transfer and a minimum of 5 years of operation. It should be noted that the actually required laser output power presumably has to be considerably higher, in order to account for losses in optical and opto-electronical components installed between laser and optical bench, such as EOMs, optical isolators, and switches for the implementation of redundancy.

Concerning the operational power stability over the LISA measurement band, typically specified in terms of relative intensity noise (RIN), requirements are imposed by the following effects:

- Proof mass acceleration noise caused by light pressure from the interferometric readout of proof mass movements (“optical readout”).
- Coupling of power fluctuations to frequency fluctuations in the laser system.
- Coupling of amplitude noise to phase noise in the photodiodes, transimpedance amplifiers, or possibly the phasemeter.

Assuming a readout power of 100 µW and normal incidence of the readout beam on the proof mass, a RIN level of approx. $10^{-3}/\sqrt{\mathrm{Hz}}$ would be sufficient to meet the acceleration noise budget of $3.4 \times 10^{-16}\,\mathrm{m/s^2}/\sqrt{\mathrm{Hz}}$ for contributions due to laser power fluctuations. However, it is expected that nonlinearities in the laser itself as well as in detectors and subsequent electronics will set a much more stringent limit, so that an active stabilization of the laser power is considered mandatory.

2.2. Spectral Properties

Independent of the actually chosen laser architecture, it will be necessary to improve the free-running phase noise of the laser system significantly in order to achieve the required detection sensitivity. This will be accomplished in several steps:

- Step 1: Frequency pre-stabilization of the laser system to an adjustable frequency reference. Functionally, this frequency reference still belongs to the laser system.
- Step 2: Further reduction of residual frequency fluctuations by arm-locking [2].
- Step 3: Algorithmic suppression of remaining phase noise by time delay interferometry [3].

The share between the individual steps is in principle flexible and still under discussion. Of relevance for the design of the LISA laser system are the first two steps, for which one or several appropriate frequency actuators have to be foreseen. A system-inherent requirement on frequency stability is required for the first step. Based on an estimation of the available arm-locking gain, a frequency noise level of

$$30\,\frac{\mathrm{Hz}}{\sqrt{\mathrm{Hz}}} \times \left[1 + \left(\frac{1\,\mathrm{Hz}}{f}\right)^{1.5}\right] \tag{2}$$

is currently considered to be adequate over the LISA measurement band for the pre-stabilized laser system. Aliasing effects might necessitate a future extension of this requirement to high frequencies above 1 Hz.

The high spectral purity has to be combined with sufficient coarse tuning capabilities to ensure the phase locking capability between all lasers in the LISA constellation. The required overall tuning range is thus mainly given by the manufacturing tolerances between the individual lasers. In case an optical resonator is utilized for frequency pre-stabilization, the laser system should also allow to cover at least one free spectral range of the cavity. Therefore, a total mode-hop-free tuning range of about 2 – 5 GHz seems reasonable.

3. REVIEW OF LASER ARCHITECTURE ALTERNATIVES

For providing output powers in the range of 1 W or more, two principal laser architectures can be distinguished: a single high power oscillator, or a low power oscillator with subsequent power amplifier. In both cases, the choice of oscillator design is driven by the demanding requirements on frequency noise.

A stand-alone high power oscillator for an envisaged LISA application has been developed on breadboard level in the ESA financed study "High Stability Laser for Space Interferometry" [4], led by EADS Astrium. It is based on a monolithic Nd:YAG non-planar ring oscillator (NPRO), which is longitudinally pumped by a fiber-coupled laser diode module. The system achieved an output power of slightly more than 1 W at the exit of a polarization maintaining fiber with a slope efficiency of about 42 %. By active power stabilization, a RIN level below $10^{-4}/\sqrt{\text{Hz}}$ was obtained for timescales in the LISA measurement band. An overall tuning range of roughly 30 GHz is realized by varying the temperature of the Nd:YAG crystal between 20 and 40°C, with mode-hop-free regions of max. 9 GHz. Using Pound-Drever-Hall frequency stabilization [5] to a Fabry-Perot cavity with a finesse of ~ 10.000, a frequency stability of $30\,\text{Hz}/\sqrt{\text{Hz}}$ was demonstrated for frequencies above 4 mHz.

While the HSL concept thus showed a promising performance for the purpose of LISA, it is currently not seen as the preferred architecture. In general terms, the main disadvantage of the high power NPRO design is the inherent strong coupling of spectral properties, output power, and thermal effects, which can be avoided in a master oscillator power amplifier (MOPA) configuration. Thermo-optical restrictions have so far also limited an output power scaling of Nd:YAG NPROs to power levels beyond 4 W.

In contrast, MOPA systems have demonstrated excellent spectral properties in combination with much higher optical powers. Particular attractive in the context of space applications appear all-solid-state, all-fiber solutions, which should offer superior environmental robustness and mechanical stability when compared to free space, bulk MOPA setups, due to the waveguide effect. Here, recent advances in the fiber technology as well as the availability of high power pump diodes have enabled the demonstration of continuous-wave output beyond 100 W with outstanding mode quality from single frequency, fiber amplifier based systems [6]. Crucial for this achievement has been the application of "large-mode-area" (LMA), polarization maintaining fibers, which avoid the early onset of nonlinear effects, such as Stimulated Brillouin or Raman Scattering (SBS, SRS).

Based on the master oscillator fiber power amplifier (MOFPA) approach, a detailed concept for a possible realization of the LISA laser systems will be presented in the following.

4. LISA LASER SYSTEM

A schematic of the herein proposed laser architecture for LISA is illustrated in Figure 1. As master oscillator, a low power fiber-coupled Nd:YAG NPRO laser with an emission wavelength of 1064 nm is anticipated. A suitable candidate would be the flight model utilized within the LISA Technology Package on the precursor mission LISA Pathfinder, which is currently under development. It is noted that distributed feedback (DFB) fiber lasers are likely to become an interesting alternative here in the near future.

The seed laser is protected from backward propagating signals by an in-line Faraday isolator, which is of particular importance for applications requiring low frequency and intensity noise. Subsequently, the light is coupled to a $LiNbO_3$ waveguide electro-optic modulator (EOM). For LISA, this EOM has to produce two phase modulation signals:

- A pure, sine-shaped sub-carrier at a frequency of about 2 GHz, which is required for phase noise correction of the on-board ultra-stable oscillators (USOs).
- A digital spread spectrum signal for clock synchronization, ranging and data communication between the three spacecraft. This signal resembles a pseudo random sequence at a chip rate between 2 and 5 MHz.

Placing the EOM before the amplifier allows to easily tolerate the comparatively high insertion losses, which are typically on the order of 3 to 4 dB for the fiber EOMs available today. The use of fiber EOMs offers a significant advantage with respect to power consumption, as halfwave voltages are much lower than for bulk EOMs due to the small aperture. Since for USO phase noise correction one has to rely on an accurate phase relation between sideband and carrier over the complete transmission path, it will however have to be verified that the subsequent combined amplification of all tones does not introduce intolerable excess noise.

The fiber amplifier itself consists of a double-clad, large-mode-area fiber with a polarization maintaining, typically Yb-doped active core. These fibers are commercially available today and often utilize photonic crystal technology. Pump light coupling into the core over the whole length of the fiber via the cladding ensures very high optical to optical efficiency, which is in general not achievable with bulk amplifiers, where arranging for a good mode overlap

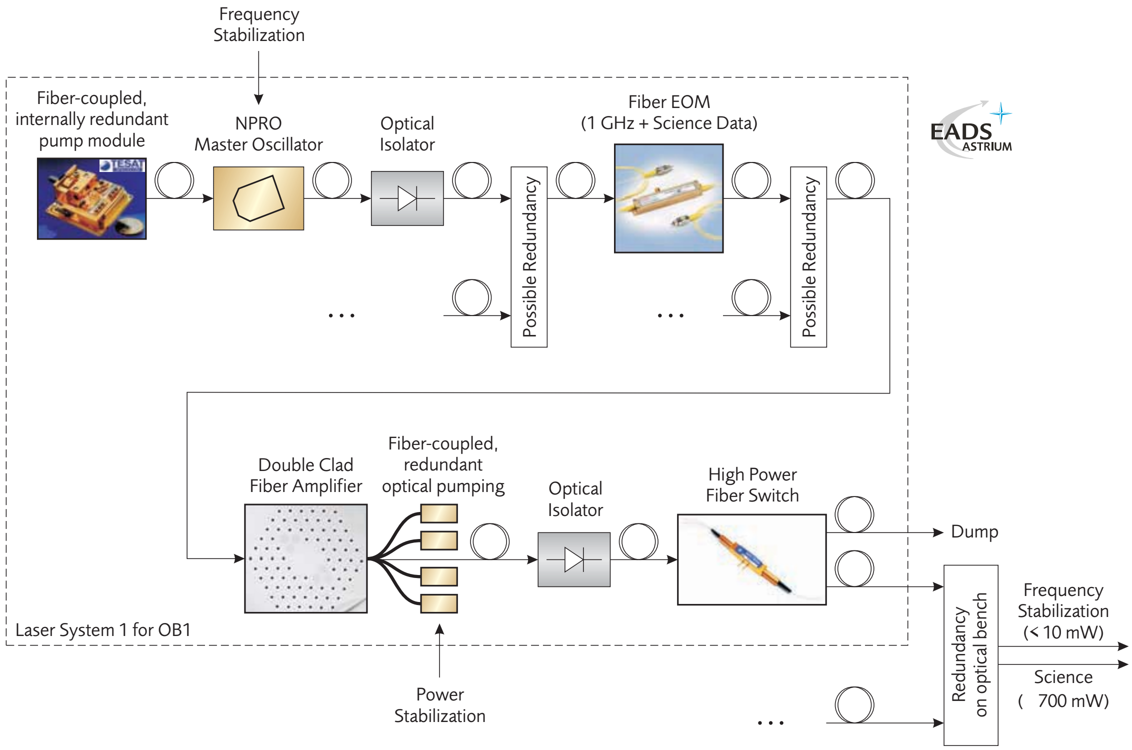

Figure 1. Overview of a possible MOFPA laser system for LISA. For concreteness, the schematic assumes the use of a low power diode pump module by TESAT for the master oscillator, a $LiNbO_3$ broadband waveguide EOM by Guided Color Technologies GmbH, and a NanoSpeed High Power 1×2 Solid-State Fiberoptic PM Switch by Agiltron.

between pump and laser light is often challenging. An end-pumping scheme can be employed with the help of a so-called octopus, which allows for direct injection of pump light from several fiber-coupled pump diodes into the cladding.

Like the seed laser, the fiber amplifier is protected from back reflections of subsequent optical components by a Faraday isolator. Depending on the maximum output power, fiber coupled devices with sufficient power handling capability are also commercially available here. Optionally, a high power fiber switch can be implemented as last element in the laser system to allow for quick on-off switching. Such operation is for example required during the initial acquisition of the laser beams between the three spacecraft. The fiber switch would avoid repeated switching of the pump diodes in the laser system and thus extended non-equilibrium situations, which would result in excessive frequency and/or power fluctuations.

4.1. Power and Frequency Stabilization

The foreseen scheme for active power and frequency stabilization is depicted in Figure 2. Both redundant laser systems for each optical bench would utilize the same set of detectors.

For power stabilization, a small fraction of the light delivered to the optical bench is monitored by a dedicated medium bandwidth photodiode. The obtained response is compared to a stable voltage reference for generation of an error signal. This is ideally applied via an appropriate loop amplifier to control the current in the pump diodes of the fiber amplifier. As this would be operated close to saturation, feedback to the pump of the seed laser would have a much weaker effect.

Frequency pre-stabilization to the required noise level should be possible by Pound-Drever-Hall stabilization to an optical resonator located on the corresponding optical bench. An according optical setup with a linear cavity is schematically shown in Figure 3. Since a short-term laser linewidth in the range of a few tens of Hz has to be achieved, the cavity linewidth should not be larger than 100 kHz, assuming that a proper loop design will allow for a gain of more than 1000. With a typical free spectral range of about 1 GHz, the cavity finesse thus has to be at least on the order of 10.000, which already requires special, ultra low loss mirrors.

One of the cavity mirrors will have to be attached to a piezoelectric transducer, so that the resonance

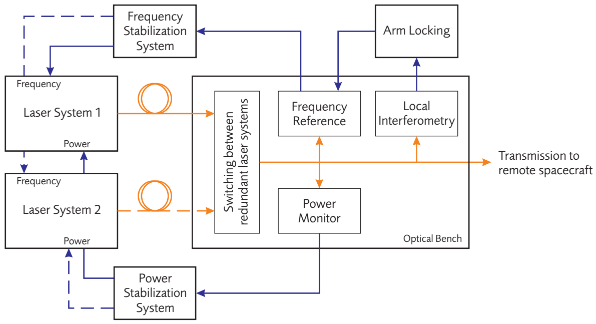

Figure 2. Frequency and power stabilization scheme.

frequency of the resonator can be adjusted for phase locking between all lasers, as explained above. The PZT should allow for tuning of more than one free spectral range, so that all laser frequencies can be covered without gaps. This however puts exceptional demands on the stability of the applied voltage, since the resulting dynamic range is extremely large: the tuning range is more than 1 GHz, while the required frequency stability is $30\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$.

A Pound-Drever-Hall error signal should in principle be obtainable from the 2 GHz sub-carrier modulation sidebands, so that no additional phase modulation is required. It will be applied to a piezoelectric transducer exerting pressure on the Nd:YAG crystal of the master oscillator. This standard procedures allows small-signal frequency corrections with a bandwidth of up to 100 kHz. In general, these corrections are maintained also in the subsequent amplification process. Nonetheless, the fiber amplifier still adds a certain amount of excess noise. Whether this will still be negligible for the purpose of LISA when compared to the phase noise performance required from arm locking has to be assessed experimentally. First results however are encouraging [7].

4.2. Redundancy Scheme

The chosen laser architecture offers the flexibility to implement redundancy on several levels. Of high importance is a sound redundancy scheme for a possible failure of the pump diodes, which are the most lifetime critical elements of the laser system. For the master laser, various, partially patented concepts for an internally redundant, fiber coupled pump unit are existing. Typically, various independent laser diodes or diode bars are optically coupled in cold redundancy into a common fiber here. For the fiber amplifier, an equivalent principle can be realized by the use of the octopus in a conceptually simple and elegant way.

Additionally, the setup leaves the option to include redundancy at further canonical points, as indicated in Figure 1. For example, a fiber switch or a fiber

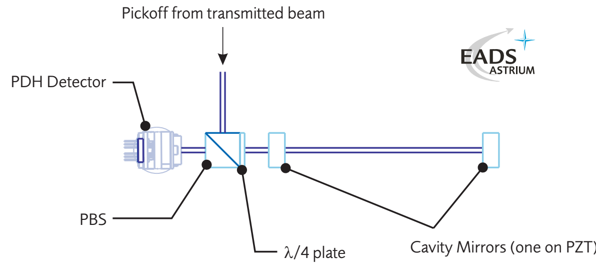

Figure 3. Typical setup for frequency stabilization to a cavity reference. The setup would be installed together with all interferometers on the optical bench. It would thus profit from the high dimensional stability provided by the Zerodur baseplate and the exceptional temperature stability of $10^{-5}\,K/\sqrt{Hz}$.

coupler can be used to add a redundant master oscillator to each laser system or realize a cross-over between the master lasers of the nominal and the redundant laser thread for each optical bench. The same is in principle possible for a backup of the EOM. Like this, the architecture allows to modularly adopt the redundancy scheme to future assessments on the reliability of individual components.

On the optical bench, switching between the two redundant laser systems can be realized in several ways, e. g. by folding away a mirror at which they are combined. Due to the stringent requirements on the thermal, electromagnetic, and gravitational environment in the vicinity of the proof mass assemblies, however, bulky mechanisms with large moving parts are to be avoided on the LISA optical benches. An attractive alternative is the use of a specialized bistable fiber switch, like the one illustrated in Figure 4. It exchanges the fiber of the nominal laser system with that of the redundant one, such that a common collimating lens can be used. Only a very small translation of moving parts therefore is necessary, which can be actuated by a mechanically amplified stack piezo. If required, the stop position could be fine-tuned by additional piezos to allow for an inflight realignment.

5. SUMMARY AND OUTLOOK

In summary, we have presented a detailed proposal for the realization of the LISA laser system, in close connection to the current payload architecture. The all-solid state, fiber-amplifier based architecture offers a high flexibility in terms of output power scaling, adjustment of spectral properties, feedback capabilities, and redundancy schemes for an adoption towards a future consolidation of the mission formulation.

The conceptual phase needs to be followed by an experimental investigation of certain concepts with the

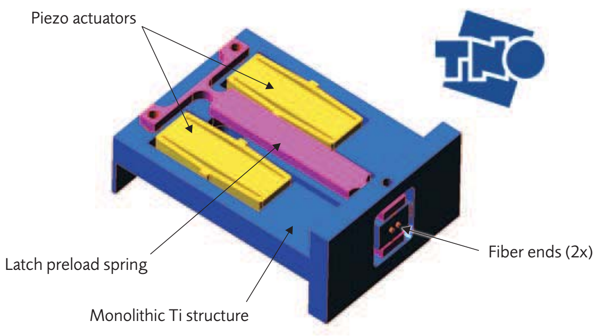

Figure 4. Conceptual design of a bistable fiber redundancy switch for integration on the LISA optical benches.

goal of the development of an engineering model. We propose in particular to verify the complete stabilization scheme, including the adjustable frequency reference, as well as to assess the impact of the chosen EOM location on the relative phase noise between the modulation sidebands and the carrier. It is noted that these aspects are closely linked to the final laser design and should not be considered independent.

6. ACKNOWLEDGMENTS

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