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Electro Optic Modulators and Modulation for Enhanced LIGO and beyond

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Abstract: The Laser Interferometer Gravitational-Wave Observatory (LIGO) is currently undergoing an upgrade to improve its sensitivity. The laser power will increase to 30 W, leading to stronger requirements on the modulators for avoiding losses and thermal lensing and also with respect to creating multiple sidebands.

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LIGO - The Laser Interferometer Gravitational-wave Observatory

Gravitational waves (GW) were predicted by Einstein [1] in 1916 as propagating fluctuations in the curvature of space-time. They are emissions from accelerating non-spherical mass distributions. Gravitational waves travel at the speed of light and are quadrupolar distortions of distances between freely falling masses. Their amplitude is measured as a "strain", defined as $h = \Delta L/L$, with L being the distance between two masses. A Michelson-type interferometers is well suited to detect these space-time distortions. To emphasize the exceedingly high accuracy in the sensitivity to length changes that is needed to detect a gravitational wave the effect from a hypothetical binary neutron star system in the Virgo cluster can be estimated to $h = \Delta L/L \approx 10^{-21}$ or approximately $4{\cdot}10^{-18}$ m for the LIGO detector with 4 km long arms.

The Laser Interferometer Gravitational-wave Observatory (LIGO) [2], consisting of three interferometers at two LIGO observatory sites (Livingston, LA and Hanford, WA) is operated by the LIGO Laboratory; the science is done by the LIGO Scientific Collaboration (LSC). LIGO finished its fifth science data run (S5) in November 2007, taking a full year of data with all three detectors running in parallel at full sensitivity. Due to the stringent requirements at the data quality this science run took two years calendar time and the recorded data is currently being analyzed.

LIGO and its three detectors are part of a world wide network of detectors looking for gravitational wave emissions from astrophysical sources. The optical path length changes originating from gravitational waves are extremely small. Measuring them requires an exceedingly high accuracy in the sensitivity to length changes.

Each LIGO detector is a power-recycled Michelson Interferometer with Fabry-Perot cavities in the 4 km long arms. All optical elements, and the laser beam between them, operate in ultra high vacuum (UHV). To decouple the environment from the position of the test masses each mirror is suspended as a pendulum from vibration-isolated platforms [3]. The suspension fiber is a steel piano wire passing under the optic as a simple loop. The sensitivity of the LIGO interferometers has been rapidly increasing over the recent year and has with S5 reached its projected design sensitivity. This sensitivity corresponds to a range of approx 15 MPc for detecting Neutron star inspiral events.

Upgrades for LIGO

After having finished the S5 science run, LIGO is being upgraded to an enhanced configuration (eLIGO), that will include among other things an increase in laser power from 8 W to 30 W. This upgrade will double the detection range for Neutron star inspiral events, to about 30 MPc, and thereby increase the probability to detect such events by a factor of eight. While currently the eLIGO upgrade is underway, R&D on the next generation of LIGO has already started, Advanced LIGO is planned to operate at power levels of 200 W and has a projected Neutron star inspiral range of 175 MPc. The increased power level poses a variety of problems for the input optics as well as for the core interferometer, but this paper will only concentrate on the phase modulators.

Phase modulators for high intensity laser beams

At the new power level, electro-optic modulators (EOMs) must be replaced – current $LiNbO_3$-based EOMs would suffer from severe thermal lensing, and possibly photorefractive effects and long term damage. The new modulators presented here are also intended to be used in Advanced LIGO and are therefore designed to be operated at 200 W while satisfying the more stringent requirements on optical modulation, including modulation frequencies, modulation depths, and relative stability of the modulation frequency and amplitude [4].

To select the electro-optics material for Enhanced and Advanced LIGO, the properties of several candidate EO materials were investigated. After a thorough literature survey and discussions with various vendors the following were chosen as the most promising materials: Rubidium titanyl phosphate ($RbTiOPO_4$ or RTP), rubidium titanyl arsenate ($RbTiOAsO_4$ or RTA) and lithium niobate ($LiNbO_3$). After corroborating lab experiments RTP was chosen as the most suitable modulator material. The standard modulator material, used in initial LIGO, lithium niobate ($LiNbO_3$), is not satisfactory from the point of view of thermal lensing, damage threshold and residual absorption.

For the realized eLIGO modulators, the crystals dimensions are 4x4x40 mm, with the long dimension being aligned to the y-axis of the crystal. The dimensions where chosen to be large enough to accommodate a high power laser beam while keeping the half-wave voltage at a reasonably low level. To avoid the unwanted generation of amplitude modulation by polarization modulation because of imperfect alignment of the incident light and also to remove etalon interference effects, we choose to wedge the faces of the RTP crystal by 2.85 degree against the z-axis of the crystal. The birefringence of the RTP material separates the different polarizations by ca. 0.5 degrees and avoids the rotation of the polarization that leads to amplitude modulation. The crystal faces are AR coated with less than 0.1% remaining reflectivity.

As a way to reduce the optical losses due to remaining surface reflections the number of modulator crystals is reduced from three to one with three separate pairs of electrodes. This still allows the application of three different modulation frequencies. The length of the center electrode is increased to achieve a stronger modulation depth.

The three electrode pairs are separately driven with a resonant circuit that is designed to have an input impedance of 50Ω. The modulation frequencies of the eLIGO modulators are 33.0 MHz, 24.5 MHz, and 61.2 MHz and with a drive power of 24 dBm for each electrode pair the corresponding modulation depths were 0.14, 0.37 and 0.14 generated. It is noteworthy that although the usage of three electrode pairs on one crystal reduces the optical losses the modulations are still applied sequentially like it would be the case for discrete modulators.

Advanced modulation configurations

Some of the interferometer control schemes that stabilize the length degrees of freedom are sensitive to the sum or difference frequencies of two modulation frequencies. This has the unwanted effect that sidebands on an already phase modulated carrier (sidebands on sidebands) create a noise term that couples into the interferometer stabilization. To avoid this currently two methods are researched, parallel modulation. The first is a Mach-Zehnder (MZ) type interferometer, used to modulate on two separated beam paths and recombine after the modulation is applied. The second method is *complex modulation*; here the sideband configuration is synthesized by using simultaneous phase and amplitude modulation. This method allows generating multiple sideband pairs without generating the mixing frequencies. The MZ modulation scheme was already demonstrated to work reliably and stable and is part of the Advanced LIGO baseline design whereas the complex modulation scheme poses more technological challenges and research is ongoing.

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