RTP: The Optics Material of Choice for the Advanced LIGO

The Advanced LIGO ushered in a new era of science – using higher sensitivities than the initial LIGO, for direct observation of gravitational waves for the first time. As part of the upgrade, the laser power of the system was greatly increased, leaving its existing LiNbO3 modulators ineffective. Raicol's RTP Q-Switch was chosen as a replacement.

The journey to success: developing the LIGO for gravitational wave observation

The Laser Interferometer Gravitational-Wave Observatory (LIGO) detects gravitational waves of cosmic origin through laser interferometry. It was built by Caltech/MIT to test a prediction made by Albert Einstein as part of his theory of relativity – the existence of gravitational waves, which provide information about movement of objects in the universe. Gravitational waves are 'ripples' in the fabric of space-time caused by violent cosmic events, like black hole collisions and star explosions.

These waves had never been proven through direct observation due to a lack of sufficient technology. Numerous interferometers were built to carry out this task, starting in the 1970s. The LIGO began its first observations in 2002. In the initial stages of operation, the LIGO didn't achieve any gravitational wave detections at all. After a period of use, it underwent a series of improvements, in hopes of eventual success. Many enhanced versions of the LIGO were developed along the way, with each component redesigned and upgraded to increased system sensitivity and accuracy. For example, the LIGO's test masses are mirrors. The distance between these mirrors is measured using a laser, but laser photons can cause a recoil effect, distorting readings. The mirrors were made larger to reduce this distortion. The LIGO's suspension was also improved to further reduce noise, using a series of pendulums and passive/active seismic isolation mechanisms that enabled vibrations to be reduced to a minimum. The 'Advanced LIGO' began its first formal science observations in September 2015 with four times the sensitivity of the original LIGO interferometers.

After just a few months, the LIGO team was thrilled to announce the Advanced LIGO's first detection of a gravitational wave, a real milestone for science. This initial detection was followed by multiple detections throughout 2016 and 2017, each one providing more insight into the nature of gravitational waves. These detections were considered a remarkable accomplishment – not only proving the existence of gravitational waves for the first time, but also confirming the predictions of general relativity. The waves themselves are so small that Albert Einstein doubted they would ever be detectable. For example, the first detection (known as GW150914) changed the length of a 4-km LIGO arm by a length equivalent to 1/1000 of the width of a proton. Detection of these waves ushers in a new era where cosmic collisions will be directly observable for the first time through gravitational wave astronomy, allowing us to gain information about the universe and its history as we observe far back in time.

The Advanced LIGO system and its optics

The LIGO is a large gravitational wave observatory in the USA, consisting of two laser interferometers located thousands of kilometers apart - one in Louisiana and the other in Washington State. The interferometers consist of two perpendicular arms (each one 4km long), along which a laser beam is shone and reflected by mirrors at each end. If a gravitational wave passes by, the arms of the interferometer alternately lengthen and shorten due to the stretching and squashing of space – causing the laser beams to travel different distances – so that they are no longer "in step" – creating an interference pattern. This effect is tiny – but the LIGO's advanced technology can still measure it. Thanks to years of research and advancements in this field of science, the team of LIGO scientists is able to recognize the patterns in arm length changes expected from gravitational wave.

Upgrading the sensitivity of the LIGO detectors for the Advanced LIGO involved increasing the laser power from the initial value of 10W to about 200W. As can be expected, the input optics needed improvement to accommodate this high power operation. The length and alignment sensing schemes of the LIGO rely on the optical sidebands generated by electro-optic modulators. The original electro-optic modulators ($LiNbO_3$ modulators) needed replacement, as they would otherwise suffer from severe thermal lensing, damage, and residual absorption – rendering them unsatisfactory. After lab experiments and consultation with Crystal Associated and Raicol Corporation, the decision was made to use a Raicol RTP crystal Q Switch.

"For a highly sensitive and powerful laser system like the Advanced LIGO, a modulator that can withstand the power without thermal lensing or damage is a necessity," said Mr. Yehiel Plaut, VP Sales & Marketing at Raicol. "The RTP Q-Switch meets this requirement."

Rubidium Titanyl Phosphate ($RbTiOPO_4$ or RTP) brings a set of benefits over the $LiNbO_3$, allowing the Advanced LIGO to operate at high laser power levels without experiencing thermal lensing or damage, **c**ontributing to the overall success of the system.

Why RTP over $LiNbO_3$? When it comes to optical absorption, $LiNbO_3$ has a much larger optical absorption than RTP, resulting in much stronger thermal lensing. Also, $LiNbO_3$ experiments have revealed a large ellipticity in beam profile, and occasional surface damage at high power levels - making it not sufficient as a modular material for the Advanced LIGO.

The lifetime of RTP crystals is mainly due to its high resistivity (in the range of 1011 ohm/cm), making the crystal suitable for EO Phase Modulation.

Compared to $LiNbO_3$, RTP has a far smaller absorption coefficient. RTP's total absorption coefficient is as low as 50ppm/cm, including scattering and 2nd harmonic generation. This leads to a focal length of the induced thermal lens of about 200m, which represents a sag change of less than 0.5% of the wavelength, at a power of about 200W.

Studies of RTP thermal lensing showed no difference in the beam waist position or beam divergence at 1W and 30W, and only a very slight decrease in divergence angle at 60W. However, the measurement error in the experiment was greater than this observed change – allowing an overall conclusion that there is no thermal lensing observable within the measurement accuracy. The RTP-based electro-optic modulators can withstand several hundred watts of continuous laser power without degradation to the beam profile.

RTP has a much higher damage threshold than $LiNbO_3$, over 600 MW/cm2 when AR coated, compared to just 280 MW/cm2 for $LiNbO_3$. When subjected to 90 W of 1064 nm light for 300 hours, RTP crystals showed no changes at all, including no damage, and no induced absorption. Based on the power and intensity of the laser beam in the LIGO, the RTP Q-switch, and its coating, is unlikely to be damaged at all during laser operation. This is compared to $LiNbO_3$, which, as mentioned before, showed damage at power levels over 30 W.

RTP: An important ingredient for the future of science

With the RTP Q-Switch, the Advanced LIGO's high power lasers could perform their job, recording gravitational waves for the first time in history. All involved were thrilled to play an important part in this exciting project, contributing to cutting-edge science, and being part of a future where we can learn about the universe and its history in more ways than ever before.