Chapter 6

Summary and Conclusions

Gravitational waves are the classical predictions of Einstein’s general theory of relativity. The existence of GWs are due the dynamics of very early universe and the various astrophysical objects. Therefore the GWs supposed to exhibit a wide spectrum of frequency $10^{-19}$ Hz to $10^{10}$ Hz. Since the relic GWs were generated in the early universe it can provide valuable information in understanding the early physical conditions of the universe impartially. Therefore investigation of the relic gravitational waves is paramount relevance in cosmology. At a glance, the relic GWs were mainly generated during the inflationary period of the early universe. Therefore the detection of the GWs not only verify the classical prediction of general relativity but also the inflationary scenario itself. There are several on going missions to detect the GWs but not realized its existence directly yet, however it is promising in near by future.

The GWs generated during the inflationary period are believed to be non thermal in nature as the models are energetically not in favour to create them. However the existence of GWs with thermal features is not ruled out completely due to several scenarios such as pre-inflationary period, extra dimensions, evaporation of mini black holes, Dirac hypothesis, etc. Even, due to the stimulated emission process during the inflationary period is also not ruled out the creation of thermal GWs. The thermal GWs can contribute
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to its amplitude and hence the spectral energy density.

The amplitude of these waves to be observed today depends on the evolution history of the universe because the universe dominated with different form of energy at its various epoch. Therefore it is interesting to study the contribution of the thermal gravitational waves to its spectrum in the present universe. The inflation era and subsequent stages, including the reheating stage, of the universe played an important role on the amplitude and hence spectral energy density of the relic GWs. The other reason to consider the GWs in thermal state is due to result of the various missions that measured the CMB anisotropy show that there exist a discrepancy between the theoretical and estimated $B$ mode angular power spectrum.

The GWs are considered in thermal vacuum state and its amplitude and spectral energy density are computed for the accelerated as well as decelerated flat FLRW universe. It is found the amplitude of spectrum get enhanced, in general, due to the contribution of thermal waves irrespective of the accelerated or decelerated model. This enhancement is the new feature of the spectrum GWs. It is observed that the inclusion of the very high relic thermal GWs due to extra dimensional effect leads to a discontinuity in the amplitude of the spectrum, at $\nu_s$. This problem is solved by deriving a new equation of line and consequence is the enhancement of the amplitude in the high frequency range ($\nu_2 \leq \nu \leq \nu_s$). This is the new feature of the spectrum and designated it as the ‘modified amplitude’. The modified amplitude of the spectrum is compared with the sensitivity of the gravitational waves detectors, Adv.LIGO, ET and LISA and shows that the modified amplitude is unlikely to detect with its current stands of Adv.LIGO and LISA but be possible with ET. Thus the existence of the thermal GWs may be verified in future and therefore some light on the extra dimensional scenario also.

The spectral energy density of the GWs is estimated in thermal vacuum state for the accelerated and decelerated flat FLRW universe. It is observed that the spectral energy density gets enhanced in the lower as well as higher
frequency ranges. A comparative study of the estimated upper bound of spectral energy density of various earlier studies with the present work is carried out. It shows that spectral energy density for the accelerated and decelerated flat universe are less than the estimated upper bound of the previous studies. The total estimated value of GWs by including the very high frequency thermal relic GWs does not alter the upper bound of the nucleosynthesis rate. Thus the relic thermal gravitons with very high frequency range are not ruled out and is testable with the upcoming data of various missions to detect GWs.

Recently, discussed that it is possible to estimate the reheating temperature of the universe with GWs. It is shown that the reheating temperature is much lower than the estimated from inflation. The scenario of the lower reheating temperature of the universe is currently under the investigation with GWs detectors BBO, DECIGO and etc. Thus, an estimate of the spectral index of reheating (z-stage) with the low reheating temperature for the non-thermal GWs in vacuum state is obtained. Hence, obtained the corresponding upper bound on the spectral index of inflation for the decelerated and accelerated flat FLRW universe and thus the amplitude of the GWs spectrum. The computed GW spectrum exhibit a dip in the higher frequency range ($\nu_s \leq \nu \leq \nu_1$) and is the feature of the reheating stage on the spectrum. The spectral energy density is also computed with new estimated values of spectral index of the reheating stage and shows that the upper bound of total spectral energy density shift to the new upper bound.

The angular power spectrum of $B$ mode polarization of the CMB is obtained in thermal squeezed vacuum state. The obtained power spectrum is found enhanced in the thermal squeezed vacuum state compared to the theoretical zero temperature case. The spectra for the two comoving temperatures are obtained, and observed that the $B$ mode correlation to be within the WMAP 7-year bound then the associated squeezing parameter and angle are to be tuned accordingly. The $B$ mode angular power of the
zero temperature case is recovered in absence of temperature and squeezing. In the present study, it is observed that the $B$ mode angular power spectrum of CMB get enhanced for all the multipole moments, higher than or equal two, in the thermal squeezed vacuum state than the previous study where the enhancement shown only for few multipole moments. The nature of the $B$ mode power spectrum depends on competition between the squeezing and thermal effects in a manner which dominates over the other.

The present study shows that enhancement of the $B$ mode correlation, due to the GWs in the thermal squeezed vacuum, lies well within in the current observational data of the WMAP 7-year. It is to be noted that the upper bound on the $B$ mode angular power spectrum of the CMB provided by the WMAP 7-year data not from the direct measurement of $B$ mode polarization but estimated it from the $TT$ and $TE$ power spectra. Therefore the enhancement of the $B$ mode angular power spectrum of the CMB is either observed or ruled out with the Planck and other mission data. And hence it may throw some light in understanding the existence of the GWS in thermal squeezed vacuum state also. The influence of the thermal squeezed vacuum state GWs on the various power spectra of the CMB anisotropy like $TT, TE$, etc, are also can be studied with the upcoming data of various experiments and is beyond the scope of present study.

From this present study it can be concluded that the existence thermal GWs is not ruled out completely. The detection of GWs with thermal features may provide in understanding the extra dimensional scenario also. The thermal GWs may explain the enhancement of $B$ mode angular power spectrum of CMB so that it matches with current observational results. However the existence of the thermal GWs are to be verified in future with the progressive missions to detect them.