Generation and detection of high frequency gravitational waves at intensive electromagnetic excitation

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Abstract. The ways of generating and detecting of high frequency gravitational wave in free space and in nonlinear dielectric media under intensive electromagnetic emission excitation have been analyzed. It was shown that there is the opportunity to realize the parametric process of gravitational wave generation with high frequency $\omega'_g = 2\omega_0$ due to combining of two electromagnetic waves with frequency $\omega_0$. In the dielectric medium synchronism conditions may be reached if the frequency $\omega_0$ of exciting light corresponds to so call unitary polaritons, characterized by unity refraction index. The detection of gravitational waves with frequency $\omega'_g = 2\omega_0$ may be examined by means of the third harmonic generation registration in corresponding dielectric media.

1. Introduction

Detection of gravitational waves is one of the most important problems of our time, interesting both from fundamental point of view, and also for many applications [1-7]. The existence of gravitational waves, arising from cosmic objects oscillation and disturbance, was predicted in the classical Einstein’s works. The interest in the solution of this problem has increased significantly after recently direct detection of gravitational waves [6]. The experimental results, presented in [6], consist of gravitational waves detection at relatively low frequencies (10 – 100 Hz), emitted by astrophysical bodies. The results, obtained in [6], based on laser interferometry technique with using of Michelson interferometer, first proposed and theoretically justified in [8]. Thus, the scientific and practical importance and actuality of gravitational waves detection and generation is not in doubt. In accordance with the theory, the gravitational wave radiating intensity is proportional to the frequency of the sixth powered degree (see, for example, [7]). In this connection, it is interesting to investigate the possibility of generating and detecting of the high-frequency gravitational waves. The theory [9] predicts the opportunity the registration of emitted by astrophysical objects gravitational waves at high frequency. According to [9], in cosmic space the modulation of high frequency $\omega_0$ electromagnetic star emission by low frequency $\omega'_g$ gravitational waves should take place, resulting combinational light scattering with frequency $\omega'_g = \omega_0 \pm 2\omega'_g$, convenient for detection in optical range. Besides this, high-frequency gravitational waves emission may be generated due to the parametric processes in cosmic space [8]. In this case, on the first step the gravitational waves with frequency $2\omega_0$ is emerging as the result of two-
photon absorption of intense high frequency $\omega_G$ electromagnetic star radiation. The indirect detection of such high frequency gravitational waves may be realized by the third harmonic of electromagnetic emission registration. The third $3\omega_G$ - electromagnetic emission is emerging as the result of $2\omega_G$ - gravitational wave combining with initial $\omega_G$ - electromagnetic wave. The high frequency $3\omega_G$ - electromagnetic emission may be detected by the very sensitive receiver. For effective parametric conversion processes realizing the momentum conservation laws (synchronism conditions) should be satisfied, i.e. the propagation phase velocity of initial $\omega_G$ electromagnetic radiation should be close to the phase velocity of $2\omega_G$ gravitational wave and $3\omega_G$ detected electromagnetic wave. Thus the third harmonic electromagnetic emission generation in cosmic space at long enough distance was predicted [9].

In this paper we propose the new ways for high-frequency gravitational waves generation and detection on the base of excitation of different parametric processes in dielectric media by powerful lasers sources of light.

2. To the theory of gravitational wave emission in the presence of powerful electromagnetic radiation

Gravitational waves correspond to propagation of metric tensor $g_{\alpha\beta}$ deviation $h_{\alpha\beta}$ in the space, described as [7]:

$$g_{\alpha\beta} = g_{\alpha\beta}^{(0)} + h_{\alpha\beta}; \left( A - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\alpha\beta} = \frac{8\pi G}{c^4} T^{\alpha\beta}_k.$$ (1)

The whole energy of gravitational emission depends on the quadruple mass momentum $D_{0\beta} = \int \mu (3x^\alpha x^\beta - r^2 \delta_{\alpha\beta}) dV$ and is given by the following relation, obtained by A. Einstein:

$$- \frac{dE}{dt} = \frac{G}{4c^5} \left( \frac{\partial^3}{\partial t^3} D_{0\beta} \right)^2.$$ (2)

For plane gravitational wave $h_{\alpha\beta} = h_{\alpha\beta}^{(0)} e^{i\omega_G (x - c t) / c} + [h_{\alpha\beta}^{(0)}]^* e^{-i\omega_G (x - c t) / c}$ gravitational wave emission intensity is proportional to $(\omega_G)^6$, i.e. sharply increases with frequency $\omega_G$ increase.

In the presence of gravitational field Maxwell equations have the shape [9]:

$$\nabla \times \bar{E} - \frac{1}{c^2} \frac{\partial}{\partial t} \left( \nabla \times \bar{B} \right) = 0; \quad \bar{B} = \frac{\bar{H}}{\sqrt{g_{\alpha\beta}}},$$

$$\nabla \times \bar{H} - \frac{1}{c^2} \frac{\partial}{\partial t} \left( \nabla \times \bar{D} \right) = 0; \quad \bar{D} = \frac{\bar{E}}{\sqrt{g_{\alpha\beta}}}.$$ (3)

Here $\bar{E}, \bar{H}$ are electric and magnetic fields correspondingly, and $\gamma = \text{Det} \left[ g_{\alpha\beta} \right] = 1 - h_{22}^2 - h_{23}^2$ for some polarization geometry.

Due to modulation of initial electromagnetic field with frequency $\omega_G$ by gravitational with frequency $\omega_G$ the secondary emission radian emerges, described by field $\bar{E}$. Thus we have:

$$\bar{E} = \bar{E}_0 + \bar{E}; \bar{E}_0 = \bar{E}_0 e^{i\omega_G (x - c t) / c} + (\bar{E}_0)^* e^{-i\omega_G (x - c t) / c}; \bar{E} = \bar{E} e^{i\omega_G (x - c t) / c} + (\bar{E})^* e^{-i\omega_G (x - c t) / c}.$$ (4)

From (3) and (4) equations it follows:

$$(\nabla \times (\nabla \times \bar{E})) - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} (\nabla \times \bar{E}) = \frac{1}{2c^2} \frac{\partial}{\partial t} \left( \frac{\partial}{\partial t} \bar{E} \right) - \frac{1}{2c} [\bar{H}_0, \text{grad} \bar{D}_{\alpha\beta}].$$ (5)

From relation (5) under condition, that $\omega' = \omega_G \pm 2\omega_G$, at the distance $L$ of gravitational and electromagnetic waves interaction, in [9] was obtained:
\[
\tilde{e}(L) = \frac{i}{2c} \left( \left( h_{22}^{(0)} \right)^2 + \left( h_{23}^{(0)} \right)^2 \right) \frac{\omega_g L}{\omega_0 + \omega_o} \tilde{e}_0. 
\]

(6)

Thus the task of low frequency gravitational waves detection is decided by registration of the high frequency secondary combinational electromagnetic emission, amplitude of which satisfies:

\[
\left| \frac{\tilde{e}_i}{\tilde{e}_0} \right| = \frac{2\pi G S_L}{n^2 \omega_g} \frac{\omega_o}{\omega_0 \pm \omega_o}.
\]

(7)

Now let us discuss of the high frequency gravitational waves registration, emerging during parametric processes. According to the known [9] relation for small intensity gravitational waves, it takes place:

\[
(\Delta - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}) h_k = \frac{16\pi G}{c^4} (T_k - \frac{1}{2} g_{aT}).
\]

(8)

Here \( T_k \) energy-momentum tensor, \( T = T'_0 \). Taking into account the relations (3,9), it was obtained [9]:

\[
h_k = \frac{4i\pi GW_0}{c^2 \omega_0} \left( \exp \left[ 2i\omega_0 \left( t - \frac{x'}{c} \right) \right] + \exp \left[ -2i\omega_0 \left( t - \frac{x'}{c} \right) \right] \right), \tag{9}
\]

where \( W_0 = \frac{E^2_0}{4\pi} \) - the energy density of exciting electromagnetic field. Thus at the presence of intensive electromagnetic field may be generated in space the gravitational wave with high frequency \( \omega_g = 2\omega_o \), i.e. doubled of exciting light frequency. In other words, in vacuum parametric process of electromagnetic field self-interactions with doubling of exciting light frequency is permitted in spite of inversion symmetry of vacuum taking place. The intensity of such parametric generation of gravitational waves should be proportional to the squared intensity of exciting emission as for the second harmonic generation in nonlinear crystals. Such parametric generation of high frequency \( \omega_g = 2\omega_o \), gravitational waves at long enough distance should take place only when the synchronism conditions are satisfied, i.e. momentum conservation law is fulfilled. On the other hand, the gravitational wave with frequency \( \omega_g = 2\omega_o \) may combine with electromagnetic wave with frequency \( \omega_o \), resulting third harmonic electromagnetic radiation at frequency \( \omega' = 3\omega_o \). Thus, for detecting of gravitational waves with high frequency \( \omega_g = 2\omega_o \), the electromagnetic emission at frequency \( \omega' = 3\omega_o \) may be recorded, if all synchronism conditions are proved.

Another opportunity for high frequency \( \left( \frac{\omega_o}{2\pi} \gg 100 \text{ Hz} \right) \) gravitational wave generation is at the presence of outer static magnetic field. According to theoretical works [10-11] the following equation for description of the hybrid gravitational and electromagnetic fields may be used:

\[
(\Delta - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}) a = \frac{2kH_0}{c^2} \sqrt{Gb};
\]

(10)

\[
(\Delta - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}) b = \frac{2kH_0}{c^2} \sqrt{Ga}.
\]

Here \( a \) and \( b \) characterize electromagnetic and gravitational fields correspondingly, \( H_0 \) is the value of static magnetic field, \( k \) is corresponding wave vector, \( G \) - gravitational constant. At small distance \( L \) of propagation of electromagnetic wave in static magnetic field the coefficient \( \alpha \) of electromagnetic-gravitation wave’s conversion is very small:

\[
\alpha = \frac{GH_0 L}{c^2} \ll 1.
\]

(11)
But for long distance $L$ of wave's propagation, with synchronism condition satisfying (the equality of phase velocity of gravitational and electromagnetic waves), coefficient $\alpha$ should increase. It is waited the appearance of such kind phenomenon for pulsars, characterizing of the giant static field presence.

3. Parametric process in nonlinear media under laser excitation
The using of powerful laser radiation permits now to observe [12-21] a number of nonlinear and parametric processes in dielectric media Stimulated Raman Scattering (STRS), Parametric Light Scattering (PLS), Second Harmonic Generation (SHG), Two-Photon Light Absorbance (TPLA), Two-Photon Excited Luminescence (TPEL) and others. The experimental scheme for STRS-spectra recording in crystals is illustrated by Figure 1.

![Figure 1. Experimental setup for excitation of STRS in crystals; 1 - YAG:Nd$^{3+}$ laser ($\lambda_0 = 0.532$ mkm) with frequency doubling of initial laser emission ($\lambda_0 = 1.064$ mkm); 2 - semitrasparent mirror; 3,7 - lens; 4,6 - dielectric mirrors; 5 - STRS-active crystal; 8,12 - spectrometer; 9,13 – computer.](image)

For STRS pumping, YAG:Nd$^{3+}$ laser ($\lambda_0 = 0.532$ mkm), generating ultra-short (80ps) giant pulses with 100 Hz repetition and about 1 GW/cm$^2$ light power density, have been used [16-17]. As the result of Raman Scattering excitation the several Stokes and anti-Stokes Stimulated Raman Scattering satellites in this spectrum may be recorded. From Figure 2 we can see that four Stokes and three anti-Stokes are simultaneously excited in calcite (CaCO$_3$) monocrystal. At the first stage in STRS only one Stokes line is emerging. In this case, the conservation law for energy and momentum may be described as:

$$\hbar \omega_0 = \hbar \omega + \hbar \omega_\nu; \quad \hbar k_0 = \hbar k + \hbar k_\nu.$$  (12)
With laser pulse power, increase the additional Stokes and anti-Stokes satellites are observed (see Figure 2). In this case four photon parametric processes is realized. The following conservation laws for energy and momentum for four photon parametric processes have the shape:

\[ h\omega_0 + h\omega_{2\omega} = 2h\omega_0; \quad \bar{h}k_{2\omega} + h\omega_{2\omega} = 2\bar{h}k_0. \]  

(13)

Thus, the result of Stokes (\(\omega_{2\omega}\)) and anti-Stokes (\(\omega_{\omega}\)) parametric processes excitation, the pair of free initial light quanta with frequency \(\omega_0\) are burning. Such photons are entangled, because of its simultaneous burning as the result of elemental four photon parametric process. In real crystal there is the possibility of simultaneous absorbance of Stokes (\(\omega_{2\omega}\)) and anti-Stokes (\(\omega_{\omega}\)) quanta with the emergence of scalar excitons, symmetry of which coincides with the symmetry of gravitational wave with frequency \(\omega_0 = 2\omega_0 = \omega_{\omega} + \omega_{2\omega}\). For gravitational waves, refraction index is equal to unity. Thus, such high frequency gravitational wave should be strong enough at long distance only if the corresponding momentum conservation law for such processes is satisfied. Such situation may be realized if exciting light emission corresponds to so call unitary polaritons [22-23]. For unitary polaritons in dielectric medium refraction index is equal to unity. Correspondingly in this case the phase velocity of gravitational wave (\(\omega_0 = 2\omega_0\)) and laser wave (\(\omega_0 = \omega_0\)) velocity should be the same. As the result of parametric processes of two exciting light wave combining, the generation of coherent gravitational wave at powerful enough laser pumping should take place.

Another way for synchronism conditions satisfying is the use of disordered solid sample: powder or microstructure dielectrics, non destructive at high intensity laser pumping. The experimental scheme for STRS exciting in such type samples is illustrated by Figure 3.

**Figure 2.** STRS normalized spectrum of calcite (CaCO₃) monocrystal, excited by ultra short pulses of the powerful -YAG:Nd³⁺ laser (\(\lambda_0 = 0.532 \text{ mkm}\))

**Figure 3.** Experimental setup for excitation of STRS in microcrystal powder; 1 - powerful pulsed laser, 2 - lenses, 3 - holder, 4 - STRS-active powder, 5 - spectrometer, 6 - computer. Dark circles correspond to gravitational waves.

Due to micro structured powder disordering, the photon localizing inside of the sample in the region, comparable to wavelength of exciting radiation, should take place. If the intensity of exciting laser emission is large enough, the density of electromagnetic field \(W_0\) should be very high. Thus, in the
case, satisfying to relation (9), the gravitational emission with frequency \( \omega_g = 2\omega_0 - \omega_0 + \omega_{so} \) should be generated. For detection of such type gravitational waves (dark circles at figure 3). The third harmonics generation signals should be recorded by receiver 5.

Recently [24-27] the mesoporous photonic crystals for investigations of nonlinear processes in dielectric media, embedded into voids of such type crystals, have been used. The important property of such type is the opportunity to essentially decrease of electromagnetic waves group velocity at some spectral range, near the edges of so call photonic band gap. As the result of Purcell effect (photonic density of states increase) at such conditions realizing the efficiency of nonlinear processes may be sharply enhanced [28]. The local second and third harmonic generation in mesoporous photonic crystals have been recorded [25-27] by using of femtosecond pulse laser emission with intensity at the samples up to 1 TW/cm\(^2\). So the mesoporous photonic crystals are useful objects for high frequency gravitational waves generation and detection investigations.

4. Conclusion

Thus we have analyzed the conditions of generating and detecting of high frequency gravitational wave in free space and in nonlinear dielectric media under intensive electromagnetic emission excitation. It was shown that there is the opportunity to realize the parametric process, resulting gravitational wave generation with high frequency \( \omega_g = 2\omega_0 \) due to combining of two electromagnetic waves with frequency \( \omega_0 \). In the dielectric medium synchronism conditions satisfying may be realized if the frequency \( \omega_0 \) of exciting light corresponds to so call unitary polaritons, characterized by unity refraction index. The detection of gravitational waves with frequency \( \omega_g = 2\omega_0 \) may be on the base of third harmonic generation in corresponding dielectric media.

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