GENERATION OF HIGH HARMONICS WITH MODULATION OF THE SPEED OF THE SOURCE

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As a rule, the generation of harmonics of laser radiation is realized through nonlinear effects in the medium. Here we will consider a new method for generating harmonics during the propagation of light in a vacuum, based on the ballistic theory of Ritz.

The ballistic theory, put forward by Walter Ritz in 1908, goes back to Newton's corpuscular theory of light and asserts that relative to the source, light is emitted at the standard speed **c**, and relative to the system in which the source moves with speed **V**, the speed of light is equal to the vector sum **c**+**V**. This theory explained the aberration of starlight, the experiments of Michelson, Fizeau and Sagnac. Late experiments, including the analysis of binary stars [1, 2], do not contradict it.

So, back in 1910 D.F. Comstock noted that the orbital velocity V of binary stars imparted to light would distort their apparent motion. A star flying in a circular orbit, when approaching, would send light at a speed $(c+V)$, and when moving away, at a speed $(c-V)$, introducing an extra light delay. As a result, the apparent motion of the star would differ from that prescribed by Kepler's laws, which was considered an argument against Ritz's theory. And the curve of radial velocities of the star $V_r(t)$ in the form of a sinusoid would acquire a sawtooth shape, in the first approximation resembling the velocity graph for an elliptical orbit elongated to the Earth. In 1913, astronomers P. Gutnik and E. Freundlich noted that the distortion is actually observed in the form of the Barr effect, that is, the predominance of stars with orbits extended to the Earth - with periastron longitudes ω* near 90°. Statistical analysis revealed the Barr effect in exoplanets as well. Since for their orbits high eccentricities and an inhomogeneous distribution over ω* are unlikely, it is precisely the distortion of the radial velocity curves that is observed.

The distorted radial-velocity curve corresponds to an elliptical orbit only in the first approximation, and the deviations, as noted by E. Freundlich, have the form of harmonics of the orbital period, actually discovered in stellar and exoplanetary systems. Moreover, in the latter, harmonics are interpreted as the real existence of exoplanets with periods related to the main one as 1: 2, 1: 3, 1: 4, etc. So, according to [3], the orbital resonance 1: 2 is inherent in half of the open planets. Although theoretically possible, it would be rare, and the shape of the $V_r(t)$ graphs is easier to explain not by the presence of extra planets with multiple periods, but by the modulation of the speed of light, which distorts the sinusoidal radial velocity curve. This generates harmonics, as in the klystron, which modulates the electron velocity.

The profile of an electromagnetic wave from an electron orbiting with radius R in a magnetic field would be distorted in the same way, which would cause it to radiate not only at the cyclotron frequency f_c, but also at multiple frequencies nf_c. The intensity and number n of higher harmonics should increase with an increase in the speed V of the electron and the distance L traveled by light in a vacuum. The radiation power of the harmonics will become comparable to the radiation power at f_c when the electron acceleration $a = V^2/R$ reaches the threshold $a_0 = c^2/L \sim 10^{17}$ m/s^2 (at $L \sim R \sim 1$ m), that is, at $V{\sim}c$. Indeed, at $V{\sim}c$, electrons, along with radiation at frequency f_c, generate its harmonics, which are most intense in synchrotrons, where electrons with $V{\approx}c$ generate synchrotron radiation. Moreover, to increase the signal-to-noise ratio, the radiation is output through extended evacuated channels. If for the output of visible radiation the length of the channels is $L{\sim}1$ m, then for hard X-ray radiation it is $L{\sim}100$ m [4], which is explained by the increase in the number n and the power of higher harmonics as L.

The speed can also be modulated by the pressure of laser radiation on atoms or nanoparticles, which scatter light and serve as secondary sources. The light pressure $p = 2I/c$ imparts to a spherical particle of radius $r \sim 10^{-9}$ m, density $\rho \sim 10^3$ kg/m^3 and mass $m = 4\pi r^3\rho/3$, acceleration $a = p\pi r^2/m \sim I/\rho cr$. It will exceed the threshold value $a_0 \sim 10^{17}$ m/s^2 already at an intensity $I_0 \sim 10^{16}$ W/cm^2, which is attainable in femtosecond laser pulses [5]. However, harmonics are generated at lower I, and at $I \sim I_0$ the powers contained in the harmonics nf and in the radiation of frequency f are comparable.

Consider the generation of harmonics under the action of a linearly polarized wave with fields $E(t) = E_0\sin(\omega t)$ и $B(t) = B_0\sin(\omega t)$. The light pressure p caused by the Lorentz force $F(t) \sim r^3 j(t)B(t) = r^3\sigma E_0B_0[1 - \cos(2\omega t)]/2$ changes rapidly due to the oscillations of the field $B(t)$ and the current density $j(t) = \sigma E(t)$ in a particle, modulating with a frequency 2ω the acceleration $a = F(t)/m$ and the velocity V of the particles. As a result, the profile of the wave re-emitted by conduction electrons will be distorted, assuming a shape close to the "meander" $E(t) = \cos(\omega t) - \cos(3\omega t)/3 + \cos(5\omega t)/5 - \ldots$, while the wave emitted bound electrons - a shape close to the "triangle" $E(t) = \cos(\omega t) + \cos(3\omega t)/9 + \cos(5\omega t)/25 + \ldots$. That is, the spectrum is formed by odd harmonics of the carrier frequency f, up to the limiting frequency f', corresponding to the harmonic synthesizing the steepest or sharpest portion of the $E(t)$ graph.

Note that in experiments the spectrum of attosecond pulses generated in a gas jet by femtosecond pulses is formed precisely by odd harmonics of the carrier frequency f [5]. The rapid decay of the intensity of the first harmonics is followed by their slow decay - a "plateau" similar to the asymptotic decay of $1/n$ harmonics of the "meander" and breaking off at the frequency f'. It is possible to check whether this mechanism is realized by studying the dependence of the pulse spectrum on the distance L traveled by light in a vacuum, which increases the signal distortion. And compression of a femtosecond pulse and an increase in its intensity I would lead to an increase in the frequency of harmonics above the value of nf due to the time-averaged light pressure force $F \sim r^3 \sigma E_0 B_0/2$, which accelerates particles and transforms their radiation according to the Ritz effect [2].

So, the effects of harmonic generation were predicted a century ago and received the simplest explanation in ballistic theory. If confirmed, the noted regularities will improve the efficiency of high harmonic generation.

Literature:

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