Laser excitation of the dark bound photonic states during parametric processes in dielectric media

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Abstract. Dispersion laws of darktons (non radiative quasiparticles) in vacuum and in dielectric media were analyzed. The theory of dark bound photonic states generation as the result of different parametric processes is developed. Fermi resonance condition for dark bound photonic states forming is discussed. The experimental setups for dark bound photonic states detection are proposed. The generation of coherent darktons emission by using of powerful pulsed laser as the pumping source for parametric processes excitation in dielectric media is predicted. The synchronism conditions in photon-darkton conversion processes are proved on the base of unitary polaritons (refractive index close to unity) exciting.

1. Introduction

In linear approximation photons in vacuum are non interacting between itself. However, including the nonlinear (parametric) terms in Hamiltonian, results in the photon-photon interactions. Photon-photon scattering may be described if third and fourth order parametric processes of Hamiltonian are taking into account. The interactions between photons become essential only for very intensive light emission, achievable inside of stars or with the help of powerful lasers. It is known, that in solids the strong phonon-phonon scattering due to the fourth or third order anharmonicity results in the existing of scalar or pseudoscalar dark bound states of two phonon (biphonon), non interacting with polar vibration. Accordingly as the result of the strong photon-photon scattering the scalar or pseudoscalar (nonradiative) dark bound states of two photons in vacuum may be created. Dark states of photons (hidden photons and axions) in vacuum may be called as darkton states. Darktons are massive Bose-type particles, satisfying to the known relativistic law:

$$E^2 = m_0^2 c_0^4 + p^2 c_0^2.$$  

Here $E = \hbar \omega$, $p = \hbar k$ are the energy and momentum of darktons, $m_0$ is the rest mass of darktons and $c_0$ - the velocity of light in vacuum.

According to the modern scenarios of Universe evolution the phase transition, closed to the first order type, in isotropic media, corresponding to initial physical vacuum state (praphase), has been occurred. The initial vacuum phase state of Universe (praphase) existed at very high temperature and pressure. At these conditions darktons may be formed as some soft modes, responsible for the lowering of vacuum symmetry as the result of the phase transition during temperature lowering. The so-called standard model, describing such phase transition, is based on local (gauge) symmetry with symmetry group $SU \times U(1)$. As the result of the phase transition, at lower temperatures the soft mode, corresponding to the density of matter fluctuations, was freezing and some space ordering of vacuum...
particles (maximons) was realized. Accordingly in the spectrum of elementary excitations of vacuum, the scalar type quasiparticles, known as Higgs bosons, have appeared. Such quasiparticles, corresponding to density of vacuum fluctuations, are formed as the result of bounding of two photons. In recent years it became clear that the standard model, despite of great success in the description of the known elementary particles spectrum, requires further clarification, by taking into account the effects of time (T) breaking symmetry at small distances. In this regard the theory predicts the existence another soft modes, known as Goldstone-Nambu boson. The known theory of incommensurate phase transition in solids predicts the existence of two types of soft modes, corresponding to so-called “amplitudon” and “phason”. Accordingly near the phase transition in vacuum should exist darkton (amplitudon) and darkton (phason) quasiparticles. Thus the conclusion [1-3] was made about the existence in vacuum of Bose-type particles with the very small but finite rest mass. It is so called hidden-photons (scalar-type particles) and axions (pseudoscalar type one), corresponding to soft mode excitations, responsible for the phase transition in vacuum. It is expected that the rest mass of these particles is very small. Its rest energy is at the range 0.001–1.0 meV, i.e. less than the rest mass of all known elementary particles. Hidden photons and axions may be classified as some types of darktons. Such elemental excitations have appeared in the earliest stage of Universe as the result of vacuum symmetry lowering during Universe phase transition. Now there is the preposition [4-7], that hidden photons and axions are possible elemental particles of dark matter. The problems of the presence of dark matter (total share 0.23) and dark energy (the total share of 0.73) in the Universe are actual task of the modern physics. Hidden photons and axions are predicted to be some candidates on elementary particles of dark matter. “Cold” (slow) hidden photons and axions are nonrelativistic (Newtonian) particles. “Hot” (fast) hidden photons and axions are relativistic particles and move with the speed, close to the speed of light. Important property of these particles is its super weak interaction with media. According to the estimates obtained from astrophysical data, the equilibrium concentration of hidden photons and axions in our part of the galaxy is about $10^{-24}$ g/cm$^3$. So, owing to the extremely small rest mass, these particles should be in Bose-Einstein condensate state even at room temperature. Now the task of detection and generation of darktons in the laboratory is discussed [3-7]. The theory predicts photon – hidden photon conversion in vacuum by using of intense laser emission as exciting light. Beside that, the feasibility of photon-axion conversion and inverse processes in the presence of strong external magnetic field in vacuum with using of powerful lasers is predicted. In works [3-5,7] it was suggested the possibility of “hot” axions creating with energy 2–3 eV in the laboratory as the result of photon-axion conversion in experiments as “Light shining through wall” (so-called Primakov-effect). Schematic diagram for the generation and detection of axions on the base of Primakov effect using is shown in Figure 1.

![Figure 1](image-url)  
**Figure 1.** Schematic setup for observation of the effect of photons of laser radiation conversion into pseudoscalar bosons $\gamma \rightarrow a$ (axions) and the reverse process — the reconversion $a \rightarrow \gamma$; 1 — the source of laser radiation; 2 — mirror; 3 — solenoids; 4 — opaque wall; 5 — receivers of the secondary radiation; 6 — Fabry–Pérot resonator, generating the light quanta ($\gamma$).

Taking into account the strong magnetic field presence (see Figure 1), the photon-axion ($\gamma - a$) conversion was waited. Axions, emerging at left side of setup, should penetrate through the opaque
wall 4. Then, at right part of setup, reverse processes should take place resulting axion-photon conversion. So the reconverted photons may be detected after opaque wall. As a result of the secondary photons detection the probability of these processes and effectiveness of the photon production from “hot” for axions in the laboratory may be evaluated. According to the selection rules, photon-axion conversion processes are permitted only when magnetic field, the induction of which is perpendicular to the direction of the beam of exciting radiation, is applied to the area of laser radiation. In the absence of an external magnetic field photon-hidden photon conversion processes are allowed, the probability of which is very small. As it turned out from the experiments [3-5,7], the useful signal of the secondary radiation produced as the result of conversion-reconversion processes seemed to be extremely small and the useful signal is below the sensitivity threshold of the modern detectors. So far the attempts for laboratory hopeful observation of photon-hidden photon and photon–axion conversion in vacuum were not successful because of very small photon-photon interaction efficiency in vacuum. We consider that such experiments should be continued, but not only in vacuum and also in dielectric media, where the efficiency of photon-photon parametric processes is essentially higher with comparing to vacuum. It is known, that if photons penetrate from vacuum into dielectric media some hybrid (photon-phonon) particles are formed, named as polaritons. Accordingly, when vacuum darkton penetrate into media, hybrid vacuum darkton-media scalar or pseudoscalar excitations should take place.

In this paper the properties of different parametric processes with generating of darkton-type excitations in dielectric media and in vacuum are discussed. The laboratory experimental schemes for photon-darkton conversion processes observation under intense laser excitation of parametric processes in dielectric media are proposed.

2. Polaritons as photons in dielectric media

Consider the case of cubic dielectric crystal with one polar (dipole-active) optical branch as CsCl-type. For such case the Maxwell equations are:

\[
\begin{align*}
\text{rot} \vec{E} &= -\frac{\partial \vec{B}}{\partial t}; \quad \text{rot} \vec{H} = \frac{\partial \vec{D}}{\partial t}; \quad \vec{D} = \varepsilon_0 \varepsilon \vec{E} = \varepsilon_0 \vec{E} + \vec{P}; \\
\text{div} \vec{D} &= 0; \quad \text{div} \vec{B} = 0; \quad \vec{B} = \mu_0 \mu \vec{H} = \mu_0 \vec{H} + \mu_0 \vec{M}.
\end{align*}
\]

Thus, for electric field \( \vec{E} \) of plane transverse monochromatic waves we obtain the wave equation:

\[
\left( \nabla^2 - \frac{\varepsilon \omega^2}{c^2} \frac{\partial^2}{\partial t^2} \right) \vec{E}(\vec{r},t) = 0; \quad \vec{E}(\vec{r},t) = \vec{E}_0 \exp \left[ i(\vec{k}\vec{r} - \omega t) \right].
\]

(3)

Correspondingly for dispersion law \( \omega(k) \) of transverse electromagnetic waves in such media we have:

\[
\omega^2 = \frac{\varepsilon_0 k^2}{\varepsilon(\omega)}; \quad \mu(\omega) = 1; \quad \omega^2 = \frac{\mu_0 k^2}{\varepsilon(\omega)}.
\]

(4)

Here \( \varepsilon(\omega) \) and \( \mu(\omega) \) are the corresponding dispersion dependences of dielectric and magnetic permittivity. At the first stage, we will not take into account the contribution to the dielectric permittivity of valence electrons, but analyze the dielectric properties of the medium taking into account only one polar vibration. The equation of motion of the polar vibrations has the form:

\[
\ddot{u} = -\omega_0^2 \dot{u} + \frac{eF}{m} \vec{E}, \quad \dot{u} = \ddot{u}_0 \exp \left[ i(\vec{k}\vec{r} - \omega t) \right]
\]

(5)

Here \( m \) is the oscillator effective mass, \( e \) is the electron charge, \( F \) is so called oscillator strength \((F \sim 1)\) and \( u \) is the magnitude of deviation of oscillating particle from equilibrium position, \( \omega_0 \) - is the frequency of polar oscillator. According to Eq. (5), the corresponding amplitude of the oscillating charged particle is:
\[ \hat{n}_0 = \frac{e \sqrt{F}}{m (\omega_0^2 - \omega^2)} \hat{E}_0. \]  

(6)

Correspondingly, for the amplitudes of the dipole momentum and the polarization (\(V_0\) - is the volume of elemental cell) take place:

\[ \hat{p}_0 = \frac{e^2 F}{m (\omega_0^2 - \omega^2)} \hat{E}_0; \quad \hat{D}_0 = \frac{e^2 F}{m V_0 (\omega_0^2 - \omega^2)} \hat{E}_0. \]  

(7)

Equations for polarization are written as:

\[ \ddot{\hat{P}} = -\omega_0^2 \hat{P} + \frac{e^2 F}{m V_0} \hat{E}; \quad \ddot{\hat{P}} = \hat{P}_0 \exp\left[i (\mathbf{k} r - \omega t)\right]. \]  

(8)

Introducing frequency \(\omega_h = \sqrt{\frac{e^2 F}{m V_0}}\) from Eq. (7) we arrive to the relation

\[ \ddot{\hat{P}} = -\omega_h^2 \hat{P} + \omega_h^2 \hat{E}. \]  

(9)

For the electric field induction we get the following equation:

\[ \ddot{\hat{D}}_0 = \varepsilon_0 \dot{\hat{E}}_0 + \ddot{\hat{P}}_0 = \varepsilon_0 \left[1 + \frac{e^2 F}{m V_0 (\omega_0^2 - \omega^2)}\right] \ddot{\hat{E}}_0 = \varepsilon_0 \varepsilon(\omega) \ddot{\hat{E}}_0. \]  

(10)

Thus, the dielectric function can be presented as:

\[ \varepsilon(\omega) = \varepsilon_\infty \left[1 + \frac{\omega_0^2}{\omega_0^2 - \omega^2}\right] = \varepsilon_\infty \frac{\omega_0^2 - \omega^2}{\omega_0^2 - \omega^2}. \]  

(11a)

Here \(\omega_h^2 = \omega_0^2 + \omega_p^2\). Accounting for the electronic oscillator in the elementary volume \(V_0\) results in the factorization of the dielectric function:

\[ \varepsilon(\omega) = \varepsilon_\infty \left[1 + \frac{\omega_p^2}{\omega_0^2 - \omega^2}\right] = \varepsilon_\infty \frac{\omega_0^2 - \omega^2}{\omega_0^2 - \omega^2}. \]  

(11b)

Here \(\varepsilon_\infty = n_0^2\) dielectric constant at high frequency with comparing to \(\omega_0\). Then, the dispersion relation for photon-phonon hybrid states (polaritons [8-9]) in the considered medium takes the form:

\[ \omega^2 = \frac{c_0^2 k^2}{\varepsilon(\omega) \mu(\omega)} = \frac{c_0^2 k^2}{\varepsilon_\infty (\omega_0^2 - \omega^2)} = \frac{c^2 k^2 (\omega_0^2 - \omega^2)}{(\omega_0^2 - \omega^2)}. \]  

(12)

Here \(\mu(\omega) = 1\) and \(c^2 = \frac{c_0^2}{\varepsilon_\infty}\). From Eq. (12) we arrive to biquadratic equation

\[ \omega^4 - \omega^2 \left(\omega_0^2 + c^2 k^2\right) + \omega_0^2 c^2 k^2 = 0. \]  

(13)

The exact solution of Eq. (13) defines two polariton branches:

\[ \omega_{\pm}^2 = \omega_0^2 + \frac{c^2 k^2}{2} \left[1 \pm \sqrt{1 - \frac{4 \omega_0^2 c^2 k^2}{(\omega_0^2 + c^2 k^2)^2}}\right]. \]  

(14)

For small wave vectors \((k \to 0)\) we get:

\[ \omega_{\pm}^2 = \omega_0^2 + c^2 \left(1 - \frac{\omega_0^2}{\omega_0^2}\right) k^2; \quad \omega_{\pm}^2 = \frac{c^2 \omega_0^2}{\omega_0^2} k^2. \]  

(15)
If we have several \((j = 1, 2, 3, \ldots, n)\) polar vibrations we come to the known following expression of dielectric function and dispersion law of polaritons:

\[
\varepsilon(\omega) = \varepsilon_0 \prod_{j=1}^{n} \frac{\omega_0^2_j - \omega^2}{\omega_0^2_j - \omega^2}, \quad \omega^2 = \frac{n_j^2 k^2}{\varepsilon(\omega)}.
\]  

Figure 2 illustrates the shape of polariton dispersion law at the presence of one polar phonon and one polar exciton branches in dielectric crystals.

**Figure 2.** Dispersion law of polariton in dielectric media. The lowest curve corresponds to polar phonons, the upper- to polar excitons; \(\omega = c_0 k\) – dispersion law of photons in vacuum; the points of
intersection between polariton branches and \(\omega = c_0 k\) line correspond to unitary polaritons, corresponding to refractive index equal to unity: \(n = 1\).

### 3. Darktons in dielectric medium

Instead of the three-dimensional Maxwell’s equations using, we consider the dispersion relation for polaritons for one-dimensional case taking into account the hybridization of polar oscillations with the electromagnetic field that penetrates into the dielectric medium. Then the equations of motion for polar oscillations and related electromagnetic field given by the function \(\xi(x, t)\) take the form [10]:

\[
\ddot{\xi} = -\omega_0^2 \dot{\xi} + \omega_j^2 \xi, \quad u = u_0 \exp\left[i(kx - \omega t)\right];
\]

\[
\ddot{\zeta} = -\frac{c_0^2}{\varepsilon_0} k^2 \dot{\zeta} - \ddot{\xi}, \quad \zeta = \zeta_0 \exp\left[i(kx - \omega t)\right].
\]  

Substitution in Eq. (17) the solutions in the form of plane monochromatic waves leads to the dispersion relation that coincides with Eq. (14). The resemble situation takes for polar excitons with the own frequency \(\omega_{\text{ex}} \gg \omega_0\):

\[
\omega_{\text{ex}}^2 = \frac{\omega_0^2 + c_0^2 k^2}{2} \left[1 \pm \sqrt{1 - \frac{4\omega_0^2 c_0^2 k^2}{(\omega_j^2 + c_0^2 k^2)^2}}\right].
\]  

The equations of motion for scalar type lattice oscillators, interacting with hidden photons in dielectric medium, can be written as:

\[
\ddot{y} = -\omega_0^2 s + \omega_j^2 \dot{\zeta}; \quad s(x, t) = s_0 \exp\left[i(kx - \omega t)\right];
\]

\[
\ddot{\zeta} = -\omega_0^2 \ddot{\xi} - c_0^2 k^2 \dot{\zeta} - \ddot{s}; \quad \zeta(x, t) = \zeta_0 \exp\left[i(kx - \omega t)\right].
\]
In these equations, the functions $\xi(x,t)$ and $s(x,t)$ describe the waves that correspond to hidden photons and scalar (total symmetrical type) optical phonons or excitons, respectively; the quantity $\omega_i$ characterizes the interaction of scalar excitations of media with hidden photons; $\omega_h$ is the frequency, corresponding to the rest mass of hidden photon; $\omega_{0i}$ is the frequency of fully symmetrical oscillation (optical phonons or excitons). The solutions of Eq.(19) for plane monochromatic wave are:

$$-\omega^2 s = -\omega_{0i}^2 s + \omega_h^2 \xi; \quad s = \frac{\omega_h^2 \xi}{\omega_{0i}^2 - \omega^2};$$

$$-\omega_h^2 \xi = -\omega_{0i}^2 \xi - c_h^2 k^2 \xi + \omega_h^2 s.$$

Solving Eq. (20) we obtain the dispersion relations of the waves under consideration:

$$\omega^2 = \omega_h^2 + c_h^2 k^2 + \frac{\omega_h^2 \omega_{0i}^2}{\omega_{0i}^2 - \omega^2};$$

$$k^2 = \frac{\omega_h^2}{c_h^2} \left(1 + \frac{\omega_h^2}{\omega_{0i}^2 - \omega^2}\right) - \frac{\omega_{0i}^2}{c_h^2}.$$  \hfill (21)

From these relations we have function $g(\omega)$, resemble to the dielectric function $\varepsilon(\omega)$:

$$g(\omega) = \frac{c_h^2 k^2}{\omega^2} = \left(1 + \frac{\omega_h^2}{\omega_{0i}^2 - \omega^2} - \frac{\omega_{0i}^2}{\omega^2}\right).$$  \hfill (22)

In common case of several scalar phonons (excitons) we have function $g(\omega)$ as:

$$g(\omega) = \frac{c_h^2 k^2}{\omega^2} = \left(1 - \frac{\omega_{0i}^2}{\omega^2}\right) + \sum_{i=1}^{n} \frac{\omega_{0i}^2}{\omega_{0i}^2 - \omega^2}. $$  \hfill (23)

From (22) we obtain the biquadratic equation:

$$\omega^4 - \omega^2 \left(c_h^2 k^2 + \omega_{0i}^2 + \omega_h^2\right) + \omega_h^2 \omega_{0i}^2 + c_h^2 k^2 \omega_{0i}^2 = 0; \quad \omega_{0i}^2 = \omega_{0i}^2 + \omega_h^2.$$  \hfill (24)

Solution of (24) results in two branches for hybrid quasiparticles: scalar phonons (excitons) and hidden photons:

$$\omega_{0i}^2 = \frac{\omega_{0i}^2 + \omega_h^2 + c_h^2 k^2}{2} \pm \sqrt{\frac{4 \left(\omega_{0i}^2 \omega_h^2 + c_h^2 \omega_{0i}^2 k^2\right)}{\left(\omega_{0i}^2 + \omega_h^2 + c_h^2 k^2\right)^2}}.$$  \hfill (25)

For small wave vectors ($k \to 0$) we obtain dispersion relation:

$$\omega^2 = \omega_h^2 + \omega_{0i}^2 - \frac{\omega_h^2 \omega_{0i}^2}{\omega_{0i}^2 + \omega_h^2} + c_h^2 k^2 \left(1 + \frac{\omega_h^2 \omega_{0i}^2}{\omega_{0i}^2 + \omega_h^2}\right) - \frac{\omega_{0i}^2}{\omega_{0i}^2 + \omega_h^2};$$

$$\omega^2 = \frac{\omega_h^2 \omega_{0i}^2}{\omega_{0i}^2 + \omega_h^2} + c_h^2 k^2 \left[\frac{\omega_{0i}^2}{\omega_{0i}^2 + \omega_h^2} - \frac{\omega_{0i}^2 \omega_h^2}{\omega_{0i}^2 + \omega_h^2}\right].$$  \hfill (26)

For calculation of corresponding dispersion law in common case we should use the relation

$$\omega^2 = \frac{c_h^2 k^2}{g(\omega)}; \quad g(\omega) = \frac{c_h^2 k^2}{\omega^2} = \left(1 - \frac{\omega_{0i}^2}{\omega^2}\right) + \sum_{i=1}^{n} \frac{\omega_{0i}^2}{\omega_{0i}^2 - \omega^2}. $$  \hfill (27)

4. Raman scattering on polaritons in dielectric crystals

It is well known the experimental setups for parametric scattering with polariton revealing in dielectric crystals by means of laser spectroscopy technique [8-9,11-15]. In these experiments the frequency-
angular $v(\theta)$ dependencies in Raman spectra of noncentrosymmetrical crystals were investigated. Figure 3 (a,b) illustrates such kind dependencies for GaP (Figure 3a) and IV-phase of ammonium chloride monocrystals (Figure 3b).

We can see from Figure 3(a,b), that at different scattering angles Raman spectrum have continuum nature and contain some sharp breaks (gaps). The continual curves correspond to polaritons, dispersion law of which is described by relations (12,16). In cubic GaP crystal there is only one polar mode, resulting two fundamental Raman peaks at 388 cm$^{-1}$ (TO-mode) and 402 cm$^{-1}$ (LO-mode) (see figure 3a). Beside fundamental (first order) Raman peaks there are a number of overtones as a result of phonon combining from the different points of Brillouin zone. Besides, there is the sharp peaks at 784 cm$^{-1}$ (more detail picture is in [16]), corresponding to dark ($A_1$-type of symmetry) bound state of two photons. The frequency of corresponding fundamental mode at $\Gamma$-point is 402 cm$^{-1}$ [16].

The gap on polariton curve at Figure 3b corresponds to resonance intersections of polaritons with two photon states in NH$_4$Cl-crystal. We can also see (Figure 3b) the sharp peaks, corresponding to dark (scalar-type) bound states at 2805 cm$^{-1}$ (more detail picture is in [15]). Such dark bound state attitude to $A_1$ (total symmetrical) irreducible representation and can not be explained as fundamental mode. This dark bound photonic states is enhanced due to Fermi resonance of overtones with fundamental total symmetrical mode at 3042 cm$^{-1}$. Thus scalar $A_1$-type dark bound photonic state is formed as the result of bounding of two photons, frequencies of which close to $v_{d}(F_2) = 1418$ cm$^{-1}$, presented in the fundamental spectrum on ammonium chloride (IV-phase) crystal, and Fermi-resonance conditions realizing for fundamental $v_1(A_0) = 3042$ cm$^{-1}$. Thus, if we use the powerful infrared laser, the frequency of which is close to the unitary polariton frequency for polar vibration $v_{d}(F_2) = 1418$ cm$^{-1}$ (see Figure 3b)), dark bound photons wave generation is waited with frequency value 2805 cm$^{-1}$.

**Figure 3.** Frequency-angular dependence $v(\theta)$ of polariton Raman scattering; a – the polariton Raman spectrum near the fundamental polar mode on GaP monocrystal under excitation of copper (578.2 nm) laser; b – polariton Raman spectra at the region of vibrational excitations in NH$_4$Cl by using of green (510.6 nm; up) and yellow (578.2 nm) copper vapor laser.
5. To the theory of third- and fourth-order parametric processes in dielectric media

As a result of the interaction between polaritons in dielectrics, the bound states of two polaritons may be created. Such bound states of two polaritons may be classified by some irreducible representations, presenting in vector symmetric squared presentations. For example the scalar type ($A_1$-type) of the bound states of two polaritons in dielectrics may be formed. Before the bound states of two phonons, magnons, plasmons, excitons, and other elementary excitations of condensed matter have been discussed. In this paper we have analyzed the opportunity of two photons (polaritons) bound states existing in dielectric media, including the polar crystals and photonic crystals.

At the first step, in dielectrics the interactions between polaritons, corresponding to different frequencies and momenta, may be not taken into account. At the second step we should consider such interactions. Thus, the Hamiltonian of the photon (polariton) system in dielectrics may be presented as follows [17-19]:

$$H = \sum_k E_k a_k^+ a_k + g_3 \sum_{k_1, k_2, k_3} a_{k_1}^+ a_{k_2} a_{k_3} + g_4 \sum_{k_1, k_2, k_3, k_4} a_{k_1}^+ a_{k_2}^+ a_{k_3} a_{k_4} + \ldots$$

(28)

Here $E_k$ is the energy of photons (polaritons), $a_k^+$, $a_k$ are creation and annihilation operators of photons (polaritons), and $g_3$ and $g_4$ are the corresponding coupling parameters. Photon-photon scattering in dielectrics may be illustrated by diagrams, taking into account also photon-phonon (Raman) processes (see Figure 4).

In view of the approximations used, the Bethe–Salpeter equation for the multiple scattering of two photons (polaritons) with momentum $Q$ has the solution ($\hbar = 1$):

$$G_\omega(\omega) = \frac{G_{0\omega}(Q, \omega)}{1 - g_4 G_{0\omega}(Q, \omega)}; G_{0\omega}(\omega) = \frac{\rho_{0\omega}(Q, \omega)}{\omega - E + 2i\gamma \omega},$$

(29)

Here $\rho_{0\omega}(Q, \omega)$ is the density of two-photonic states. Bound photonic states appear providing that $G_\omega(\omega)$ function has the pole. We can see that the bound state is indeed may be created for large enough $g_4$ constant. Such situation may be realized, for example, if Stimulated Raman Scattering (STRS) observed at high powerful laser excitation. The spectrum of bound states of two photons (polaritons) is described by the relation:

$$I(Q, \omega) = \frac{\text{Im} G_2(Q, \omega)}{\pi}.$$  

(30)

Figure 4. The illustration of photon-photon scattering processes, taking into account Stokes (red lines) and anti-Stokes (blue lines) Raman processes.

Taking into account the Dyson equation for interacting photons at $g_4 = 0$ and $g_3 \neq 0$, we arrive the equation:
Thus, the bound state is formed if $G_i(\omega)$ function has the pole at high enough $g_3$ constant.

6. Experimental setup for dark bound states of photons generation and detection during laser excitation in dielectric media

Under high intensity laser excitation in dielectric media some photon-phonon and photon-photon processes may be realized. The illustration of elemental Spontaneous Raman Scattering (SRS) processes is given at Figure 5. The example [20] of Spontaneous Raman spectrum in NaNO$_2$ crystal is given in Figure 6. We can see, that in this spectrum the most intensive Raman satellite, corresponding to pseudoscalar mode of $A_2$–type symmetry, is observed.

![Elemental spontaneous Stokes and anti-Stokes Raman scattering processes.](image)

**Figure 5.** Elemental spontaneous Stokes and anti-Stokes Raman scattering processes.

If the very intensive laser emission for Raman scattering excitation is used the so-called Stimulated Raman Scattering (STRS) may be observed. In this case, the intensity of one Stokes satellite becomes very large and the generation of coherent corresponding vibrational mode takes place. The most intensive mode in SRS mode has the lowest STRS threshold and may be revealed as stimulated process under powerful laser excitation. In NaNO$_2$ crystal such mode corresponds $A_2$ (pseudoscalar–type symmetry) lattice vibration (see Figure 6).

![Raman spectrum of sodium nitrite measured at frequencies up to 1500 cm$^{-1}$ at room temperature. The inset shows the low-frequency part of the spectrum.](image)

**Figure 6.** Raman spectrum of sodium nitrite measured at frequencies up to 1500 cm$^{-1}$ at room temperature. The inset shows the low-frequency part of the spectrum.
Experimental setup for STRS in crystals or powders observations is illustrated by Figure 7. Thus realizing of STRS processes in NaNO$_2$ crystal opens the opportunity to generate the pseudoscalar type darkton coherent waves in dielectric media.

**Figure 7.** Experimental equipments for Stimulated Raman Scattering registration; 1 - YAG:Nd$^{3+}$ laser (532 nm); 2,6 - glass plates; 3,7 - lens; 4 - sample holder; 5 - sample; 8,10 - minispectrometers; 9,11 - computers.

Usually the STRS threshold in molecular liquids or crystals is about $10^7 - 10^9$ W/cm$^2$. Note, that at these intensities of exciting emission others parametric processes have been observed, for example, two-photon excited luminescence (TPEL) [13,21-22].

The shape of multifrequency parametric STRS spectra, obtained by us for NaBrO$_3$ monocrystals, is given at Figure 8. We can see a number of equidistant Stokes and anti-Stokes satellites of scalar type ($A_1$) symmetry, with frequency shift about 780 cm$^{-1}$. Such excitations are not interacting with photons, having F-type of symmetry in NaBrO$_3$ crystal, but can strong interact with scalar darktons. Thus, under intensive laser emission in dielectric media some darkton-type vibrational or exciton modes may be excited. Several of these modes may be scalar or pseudoscalar type. Accordingly, such modes should strong interact with hidden photons or axions. Such type modes should be excited during STRS or other parametric processes [23-26]. Inside of the discussed dielectric media the coherent wave of darktons may be generated.

**Figure 8.** Stimulated Raman Scattering spectrum in NaBrO$_3$ crystal under powerful YAG:Nd$^{3+}$ laser($\lambda = 532$ nm) excitation.
For detection of darkton waves the same crystal (NaBrO₃) should be used. If the bound states with frequency close to $2\omega_0$ of two photons with frequency $\omega_0$ is generated under STRS processes the experimental setup, resemble to “Light shining through wall” in vacuum may be used (see Figure 9). The using of photonic crystals, filled by different dielectrics, opens the additional opportunities for bound state of photons observing. In this case the proximity of exciting laser emission frequency to the edges of photonic crystal band gaps results in the giant photon density of states and, correspondingly, increase of photon – dark bound state of two photons conversion efficiency [16-19, 27].

**Figure 9.** Experimental equipments for photon – two photon bound state – photon conversion; 1- YAG: Nd³⁺ laser(532 nm); 2 - lens; 3, 4 - samples; 5 - samples holder; 6 - minispectrometers; 7 - computer.

7. Summary

Thus it is proposed the optimization of experimental installations for generation and detection of dark bound photonic states by means of parametric active dielectric media using and application of intense laser emission for parametric processes excitation. For the generation of “hot” dark bound photonic states it is proposed to use the powerful laser with high spectral intensity in the visible or ultraviolet ranges. This ensures that the transition from the spontaneous dark bound photon states conversion to stimulated one should take place. It was shown that photon-darkton conversion efficiency may be enhanced if the frequency of exciting laser correspond to the frequency of unitary polaritons (refractive index is close to unity). In this case, momentum conservation law is not disturbed and group velocity of exciting laser wave should be very small. New opportunities opens the using of photonic crystals, proving the essential enhance of the spontaneous and stimulated parametric processes efficiency due to the known Purcell effect.

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