Paraphoton generation by the mesoporous photonic crystals

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Abstract. We propose the new solid-state technique to generate paraphotons at a laboratory. To do this, we offer the using of the polaritons’ Bose-Einstein condensation in the mesoporous aluminum oxide photonic crystal film at the photonic bandgap edge. This way, in the nearest-to-the surface pore, the synchronicity conditions are met, and, due to the high density of polariton states, the two photons-to-a paraphoton conversion is resonant.

1. Introduction
Paraphotons are “dark” axion-like particles arises by the photon coupling \[1\], Figure 1. However, the energy and the momentum conservation allows the process in the vacuum only, so the \(\gamma + \gamma \rightarrow p\gamma\) cross section is extremely small, and paraphotons haven’t been detected till now.

\begin{figure}[h]
\centering
\includegraphics[width=0.2\textwidth]{figure1.png}
\caption{Two photons-to-a paraphoton conversion.}
\end{figure}

In the paper, we propose the new way to deal with the problem: to use the Bose-Einstein condensate of polaritons at the photonic crystal bandgap edge. This way the Figure 1 conversion is resonant, and paraphoton effects are observable.
2. Theoretical analysis

2.1. General theory

The Figure 1 Lagrangean corresponding term is proportional to $E^2$, so the equation for the paraphoton field $\phi$ is

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}\right) \phi = -\frac{gm^2}{\hbar c} E^2.$$  \hspace{1cm} (1)

The solution for (1) is

$$\phi(\vec{r}, t) = \frac{1}{4\pi} \int \frac{gm^2 E^2(\vec{r}', t)}{|\vec{r} - \vec{r}'|} d^3\vec{r}'. \hspace{1cm} (2)$$

(we neglect the signal delaying because of $\vec{r} \approx \vec{r}'$ for the laboratory). This way,

$$\phi(\vec{r}, t) = \frac{gm^2}{4\pi\hbar c} \int \frac{E_0 e^{i(k\vec{r}' - \omega t)}}{|\vec{r} - \vec{r}'|} d^3\vec{r}' \hspace{1cm} (3)$$

where

$$\int \frac{e^{2ik\Delta r}}{\Delta r} dV = \int \frac{e^{2ik\Delta r\sin \theta}}{\Delta r} (\Delta r)^2 \cos \theta d(\Delta r) d\theta d\varphi = \frac{\pi}{2k^2} (\cos 2kR - 1)$$  \hspace{1cm} (4)

and $R$ is the radius of the conversion region. After all, we get the paraphotonic wave

$$\phi(\vec{r}, t) = \frac{gm^2}{4\pi\hbar c k^2} \sin^2(kR) E_0^2 e^{i(2k\vec{r} - 2\omega t + \pi)}$$ \hspace{1cm} (5)

with amplitude proportional to $\sin^2 kR$. Therefore, the maximum efficiency for the Figure 1 conversion is reached when

$$k = \frac{\pi}{2R} \equiv \frac{\pi}{a}, \hspace{1cm} (6)$$

where $a$ is the size of the conversion region.

Note, that in crystals, the (6) is the condition for the Brillouin zone’s edge [2]. So, the crystals can be used as the matched Fabry-Perot to resonantly increase the Figure 1 conversion. However, this way, there are two difficulties: 1) to generate visible-range paraphotons, the crystal lattice period $a$ must be $\sim 10^{-7}$ m, and 2) to satisfy the Figure 1 selection rules, in crystal, there must be the $a$-sized cavities. To deal with both of them, one can use the photonic crystals.

2.2. Mesoporous photonic crystals

Photonic crystals are the layered periodic structures with photonic bandgaps at the visible region due to its periodicity [3]. Nowadays, the most advanced ones are the aluminum oxide mesoporous photonic crystal films, synthesized by the aluminum anodizing at the controlled acid etching [4-9]. The films consist of hundreds Al$_2$O$_3$ layers with different porosity, but the odd (and the even) layers are the same. This assures the high optical quality for the samples: the bandgap reflectance is 99.99% or higher [10]. And at the same time, the crystals are full of matter-free cavities (see Figure 2). These make the aluminum oxide photonic crystal films ideal for the paraphotonning.

3. Simulation

We have simulated the 100-layered Al$_2$O$_3$-based photonic crystal film with all the odd layers of $a_1 = 193$ nm length and $\eta_1 = 30\%$ porosity, and all the even layers of $a_2 = 193$ nm length and $\eta_2 = 70\%$ porosity, Figure 2. To do this, we have used the finite-differentiate time-domain (FDTD) technique for the discussed 1D structure with layers’ refractive indices $n_i^2 = (1-\eta_i)\cdot n_{Al2O3}^2 + \eta_i \cdot 1.0, (i = 1, 2)$ with $n_{Al2O3} = 1.77$. 

Figure 2. Microphotography of the simulated aluminum oxide mesoporous photonic crystal film [11]: (a) top view, (b) front view.

The film’s transmittance spectrum and its FDTD simulation are presented at the Figure 3. One can see, that at $\lambda = 550$ nm (the photonic bandgap edge, see the Figure 3a), there is a resonant electromagnetic field amplification in the pores of the nearest-to-the surface crystal layer (see Figure 3b). At the same time, because of pore’s emptiness, the Figure 1 process is allowed. Therefore, in the pore, the paraphotonic conversion is the resonant one.

For example, the Figure 3b linear extrapolation gives, that the 550 nm LED 1 s crystal exposure makes the pore’s local field is $10^7$ times the source one. This way, the paraphotonic wave increases $10^{14}$ times (see $E^2$ factor in (5)). Moreover, due to the resonance’s sharpness (see the sharp bandgap edge at the Figure 3a), the mean field energy in pore is low, and the crystal doesn’t melt.

Figure 3. Photonic bandgap for the sample (a), and simulation for the electromagnetic energy within at the continuous excitation by $\lambda = 550$ nm (b).
4. Discussion

Because of the sophisticated synchronicity conditions, the invert Figure 1 process is allowed in the same media as the direct one only. So, the only way to observe two photons-to-a paraphoton conversion and reconversion resulting in the Primakoff effect [12], is the using of the two identical photonic crystals (e.g. splitted from the same one). Moreover, the crystals must be finely adjusted to the same optical axis, to satisfy the momentum conservation. Due to this, we think the best technique to observe paraphotons, is the using of the photonic crystals, doped with dielectrics with absorption band at the photonic crystal’s bandgap edge. This way, the electromagnetically induced transparency [13] can be the Figure 1 indicator [14]. Therefore, this absorption-band single-crystal scheme is preferably to the standard Primakoff one with separated generator and detector.

To differ paraphotons from the other similar solid-state particles, e.g. unitary polaritons, the mass indicator can be used (this way, the scattering scheme [15] is appropriate). According to the Figure 1, the paraphoton mass is \( m = \frac{2\hbar\nu}{c^2} = 5 \cdot 10^{-36} \) kg, while and the unitary polariton one is \( m_u \sim 10^{-34} \) kg [16]. Their spin is also differs: for the paraphoton \( J = 2 \) (as for the graviton) and the unitary polariton’s one is \( J = 1 \).

5. Conclusion

The established resonant electromagnetic field amplification in the nearest-to-the surface pore of the mesoporous photonic crystals offers the opportunity to paraphotoning at a laboratory. This way, the electromagnetically induced transparency of the doped crystals might be an indicator of the process.

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