Electromagnetically induced transparency in Ruby

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Abstract. In this paper, the authors show new results on the electromagnetically induced transparency in ruby. At the powerful laser excitation, the authors observed the room-temperature Bose-Einstein polaritonic condensation, the ruby optical over-transparency and the traces of hidden photonic states. The results are crucial to the paraphoton lasing.

1. Introduction
The crystalline ruby Al₂O₃: Cr³⁺ is a well-known optical medium widely used for lasing purposes [1]. Besides, the new data on the ruby [2] attracts the principal interest to the one as the high-potential material for the hunting for the new physics. In the paper, the authors focused on the electromagnetically induced transparency (EIT) [3] resulting to the forming of the “dark” polaritonic states [4].

2. Theory
Due to the specific field-matter interaction resulting in the EIT, let's focus on the classical ruby's valence Cr³⁺ electron oscillations at the external field $E_0e^{i\omega t}$:

$$m_0\ddot{x} + m_0\omega_0^2x = q_0E_0e^{i\omega t}.$$  (1)

Here $m_0 = 9.1 \times 10^{-31}$ kg is the electron mass, $q_0 = 1.6 \times 10^{-19}$ C – its charge, $\omega_0$ is the atom resonant frequency. One can see that the solution for (1) is

$$x = \frac{q_0E_0e^{i\omega t}}{m_0(\omega_0^2 - \omega^2)}.$$  (2)

This way the atom dipole

$$p = q_0x = \frac{q_0^2E_0e^{i\omega t}}{m_0(\omega_0^2 - \omega^2)}.$$  (3)

And the polarization (for the atom's concentration $n_0$)

$$P = n_0p = \frac{n_0q_0^2E_0e^{i\omega t}}{m_0(\omega_0^2 - \omega^2)}.$$  (4)

At the other hand

$$P = (\varepsilon - 1)\varepsilon_0E_0e^{i\omega t}.$$  (5)

By (4) and (5) the ruby dielectric permeability is
\[ \varepsilon = 1 + \frac{n_0 q_0^2}{m_0 \varepsilon_0 (\omega_0^2 - \omega^2)} \equiv 1 + \frac{\omega_p^2}{(\omega_0^2 - \omega^2)}. \]  

(6)

Because of two ruby lines, \( R_1 \) and \( R_2 \), we have to evaluate both of them. This way

\[ \varepsilon = 1 + \frac{\omega_{p1}^2}{(\omega_{01}^2 - \omega^2)} + \frac{\omega_{p2}^2}{(\omega_{02}^2 - \omega^2)} = 1 + \frac{A_1 \lambda^2}{\lambda^2 - \lambda_{01}^2} + \frac{A_2 \lambda^2}{\lambda^2 - \lambda_{02}^2}. \]  

(7)

The (7) is Sellmeier equation with known resonant wavelengths \( \lambda_{01} = 694.3 \) nm, \( \lambda_{02} = 692.8 \) nm and unknown (but equal [5]) oscillator forces \( A_1 \) and \( A_2 \). To determine them let’s rewrite (7) such a way:

\[ \varepsilon = 1 + \left[ \frac{1}{1 - (\lambda_{01}/\lambda)^2} + \frac{1}{1 - (\lambda_{02}/\lambda)^2} \right] A. \]  

(8)

The \( A \) is still needed to be evaluated. For this let's use the known ruby refractive index \( n_D = 1.77 \) [6] at \( \lambda_D = 589.3 \) nm (sodium D-line):

\[ \varepsilon_D = 1 + \left[ \frac{1}{1 - (\lambda_{01}/\lambda_D)^2} + \frac{1}{1 - (\lambda_{02}/\lambda_D)^2} \right] A. \]  

(9)

Finally, we have

\[ \varepsilon = 1 + \left[ \frac{1 - (\lambda_{01}/\lambda)^2}{1 - (\lambda_{02}/\lambda)^2} \right] \times \left[ \frac{1}{1 - (\lambda_{01}/\lambda_D)^2} + \frac{1}{1 - (\lambda_{02}/\lambda_D)^2} \right]^{-1} \times (\varepsilon_D) \]  

(10)

The plot for (10) is presented at Figure 1.

Figure 1. Ruby dielectric permittivity (10)

With (10) one can calculate the electromagnetic waves dispersion in ruby:

\[ k = \frac{\omega}{c} n = \frac{\omega}{c} \sqrt{\varepsilon}. \]  

(11)

The (11) is plotted on Figure 2. At figure we also show the line \( \omega = c \times k \) for the dispersion of the electromagnetic wave in the vacuum. The intersections are the unitary \( (n = 1) \) solutions for that the material media doesn't differ from the void.
To calculate the group velocity for light propagating in ruby, one have to evaluate
\[
v = \frac{d\omega}{dk} = \left[ \frac{dk}{d\omega} \right]^{-1}. \tag{12}\]

The plot for (12) is presented in Figure 3. The arrow marks the region near the \( R_1 \) and \( R_2 \). One can see there is the anomalous speed deceleration to the zero. It's the “stopped light” [7] or “the Bose-Einstein condensation of polaritons” [8].

The masses of the condensed light particles are [9]:
\[
m = \frac{\partial^2 W}{\partial p^2} = \hbar \times \left[ v \times \frac{dv}{d\omega} \right]^{-1}, \tag{13}\]
and presented in Figure 4. Notes the stopped light particles masses are the order of \( 10^{-34} \) kg.
To compare theory with the experimental data let's calculate the secondary emission spectrum. According to Fresnel (see [9]) at the normal incidence ($\phi = 0$) the sample reflectance is

$$R = \left| \frac{n-1}{n+1} \right|^2 = \left| \frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1} \right|^2.$$

The plot for (14) is shown in Figure 5.

3. Experiment

Our experimental setup is the standard spectroscopic one and includes the laser source (in Figure 6 on the left), the ruby rod (from our old ruby laser, on the center of photo) and the digital spectrometer FSD-8 (on the right). The experiments conducted alongside, across and backward to the rod.
At the experiment, we used the 410, 453, 527, 532, 590 and 640 nm 0.5W LEDs and the violet (447 nm) adjustable power laser. For all of these sources we have registered the transmittance, the reflectance, and the luminescence, but to not clutter the work we don't bring them here.

Let's focus on the most important results.

3.1 Bose-Einstein condensation. In Figure 7 we present the measured ruby luminescence spectrum (dots) compared with the theoretical one (line). As we predict (see Figure 3 insets and Figure 5) in ruby, there is Bose-Einstein polaritonic condensate with zero effective speed-of-light, formed near to the unitary polaritons ($n = 1$) frequency. At the experiment, it must reveal as a very bright luminescence peak. One can see in Figure 7 that the match is excellent.

![Figure 6. Experimental setup.](image)

![Figure 7. Luminescence in ruby](image)

3.2 Electromagnetically induced transparency. The next effect observed it's the EIT, occurred at the certain power threshold regardless of the exciting wavelength – Figure 8. At this figure, (a) is the 532 nm green laser-LED spectrum, (b) is the one after the ruby trespassing. Notes no-observable differences,
although 532 nm is in a ruby absorption band. Also at the photo on the Figure 6 one can see the violet laser light inside the ruby, while normally ruby is non-transparent for the violet.

![Graph](image1.png)

**Figure 8.** Electromagnetically induced transparency in ruby: 532 nm laser (a) before, (b) beyond the ruby

3.3 *Stokes – anti-Stokes correlations.* At Figure 9 we present the experimental data on Raman satellites in ruby at EIT by the violet laser pumping. Grayline is for the half laser power, black is for the full one. Satellites are normalized to the Stokes one. Notes the surprising (×2) anti-Stokes rising in comparison to the Stokes (marked).

![Graph](image2.png)

**Figure 9.** Raman satellites in ruby at EIT by various laser excitation power

4. **Discussion**

The results obtained can be interpreted following way. We think (but deeper researches are essential) that at the powerful laser excitation, there is the ruby ($R_1, R_2$) doublet Zeeman overlapping resulting to the Bose-Einstein condensation of polaritons near the unitary polaritons frequency. As a result, the synchronicity becomes fulfilled and the two photons pairing are allowed (Figure 10). The newly formed
particle, paraphoton, is a “dark” one, in the sense that it won't interact with the matter so the medium becomes transparent even at the absorption spectral band (see Figure 8).

![Figure 10. Two photons to a paraphoton pairing](image)

Because of the same crystal propagation, the decay probability is equal to the nascence one, but the decayed photons must not be the same. In fact, they can be, for example, Stokes and anti-Stokes ones [10]. So the non-equilibrium anti-Stokes rising at the Figure 9 indirectly confirms the photons pairing following by the Stokes – anti-Stokes decay appears over the standard Raman scattering.

However, we understand the subtlety of the theme so we are going to conduct the more specific experiment on the direct Primakoff effect observation [11] to make the conclusions.

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