Polaritons in a nonideal periodic array of microcavities containing ultracold quantum dots

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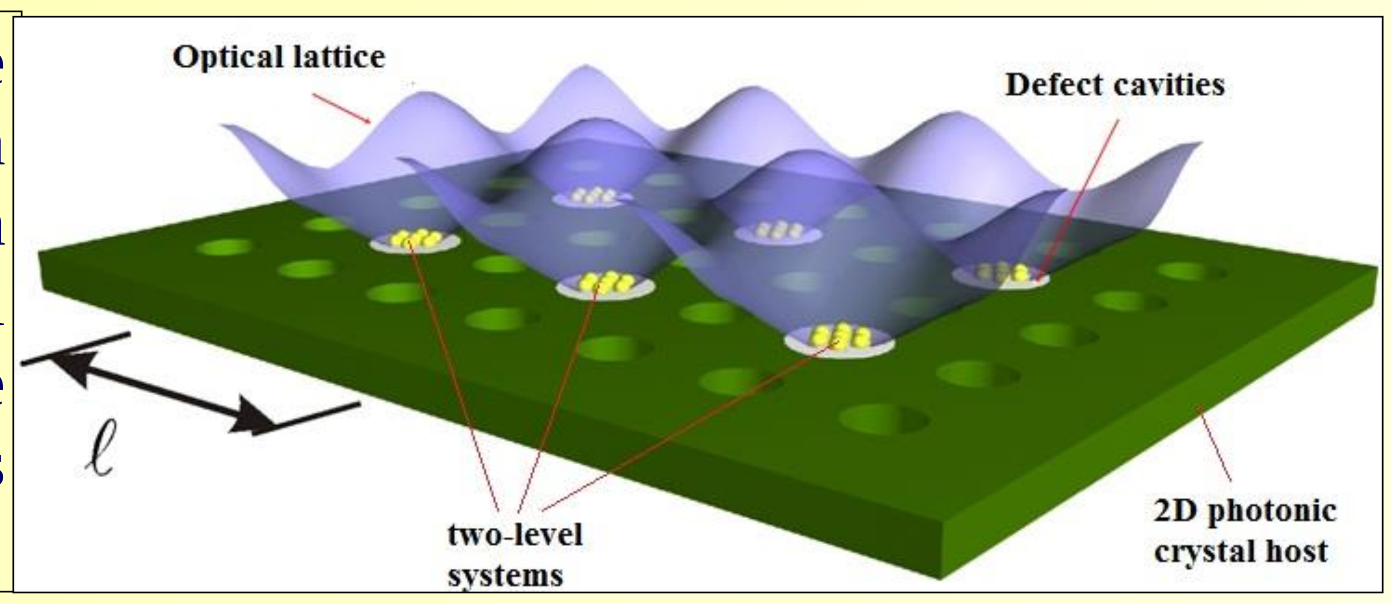
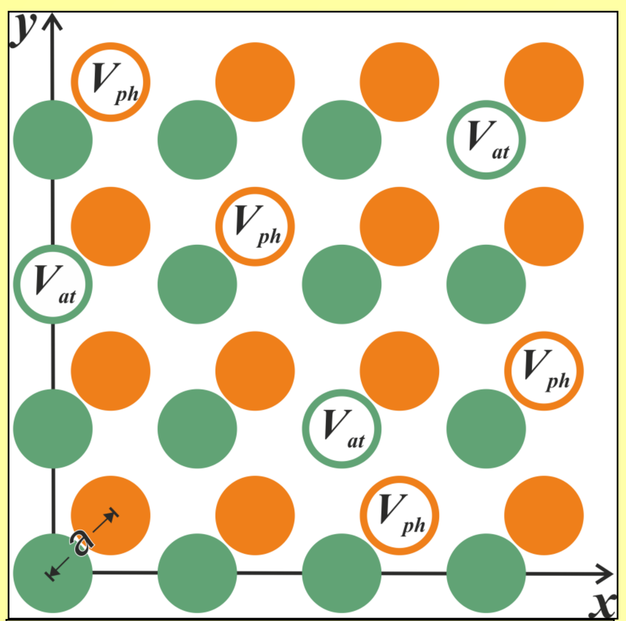
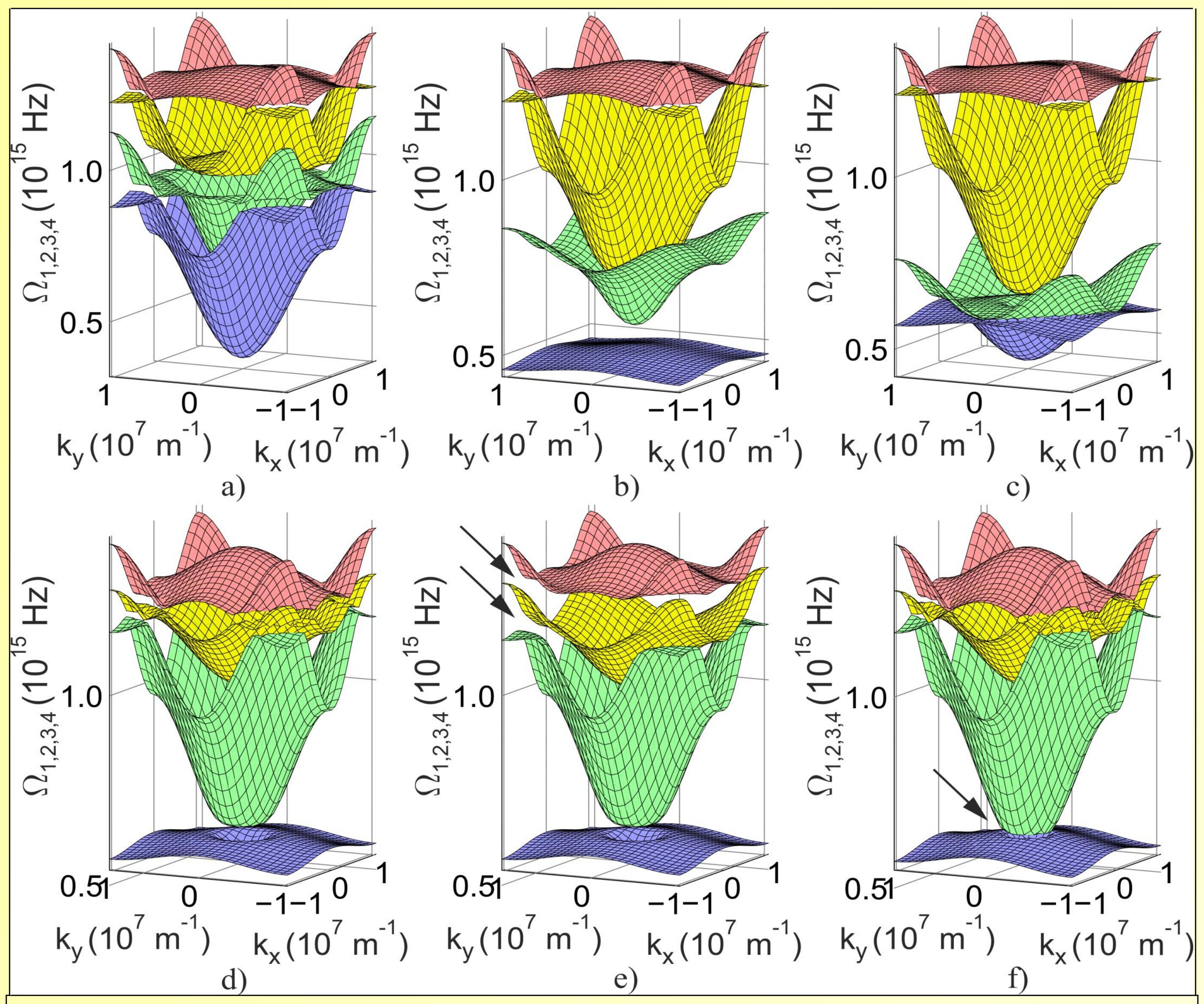
The previously developed concepts of nonideal photonic structures [1-3] are used to examine a two-sublattice defect-containing polaritonic crystal formed of a topologically ordered array of tunnel-coupled microcavities (microresonators) with embedded two-level atomic clusters (quantum dots). The virtual crystal approximation is employed to elucidate the effect of point-like defects on the polaritonic spectrum of the structure and the related quantities of interest (such as the densities of states of polaritons).

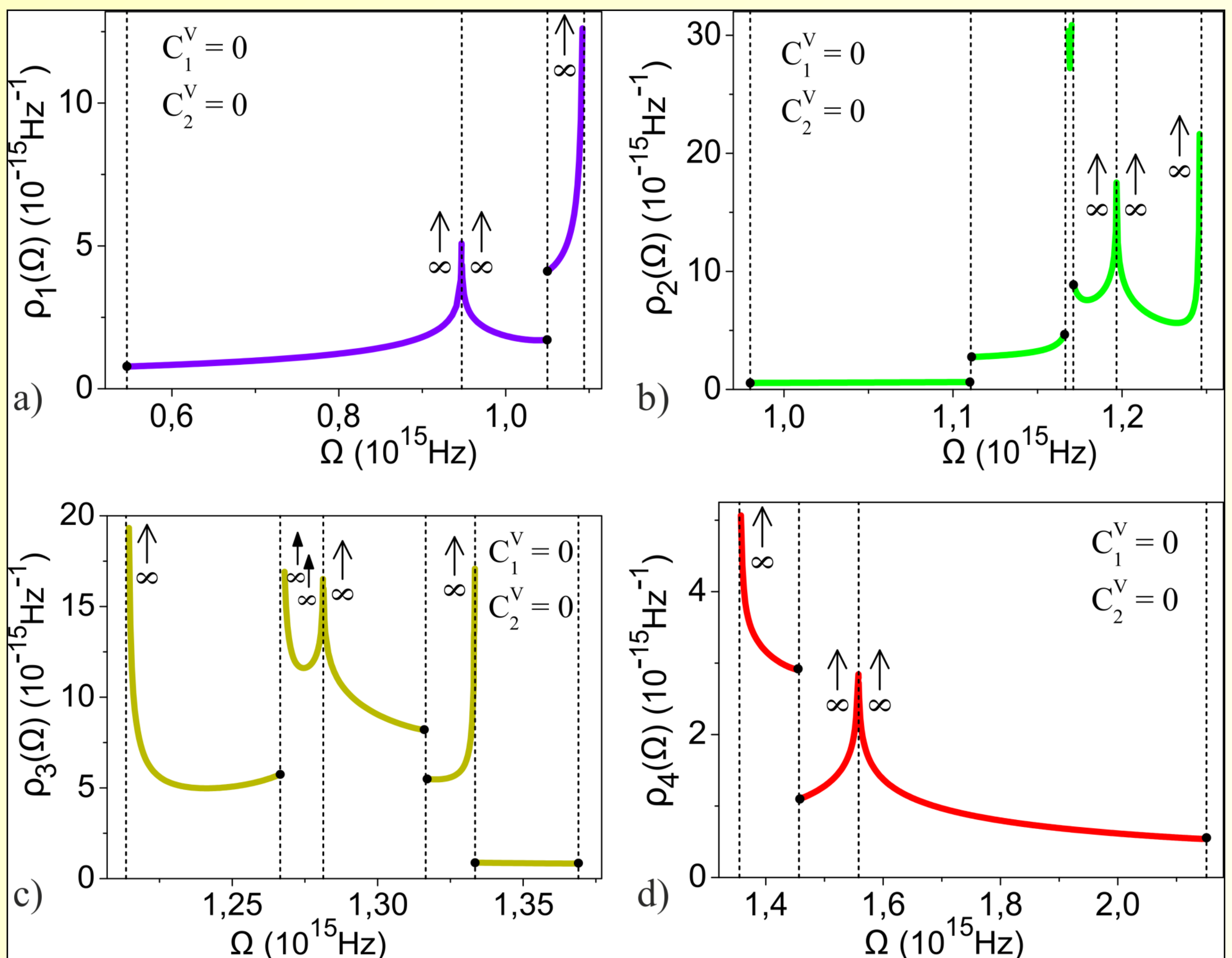




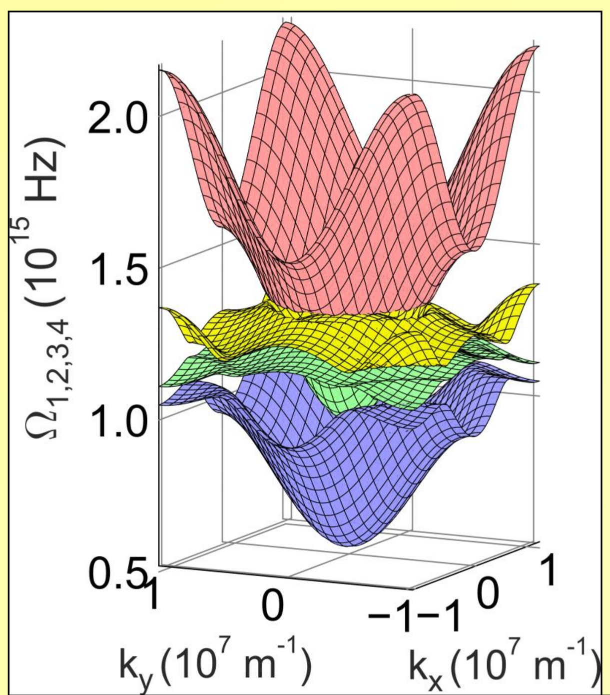
Schematic of a two-sublattice polaritonic crystal with vacancies in the atomic (Vat) and resonator (Vph) subsystems.



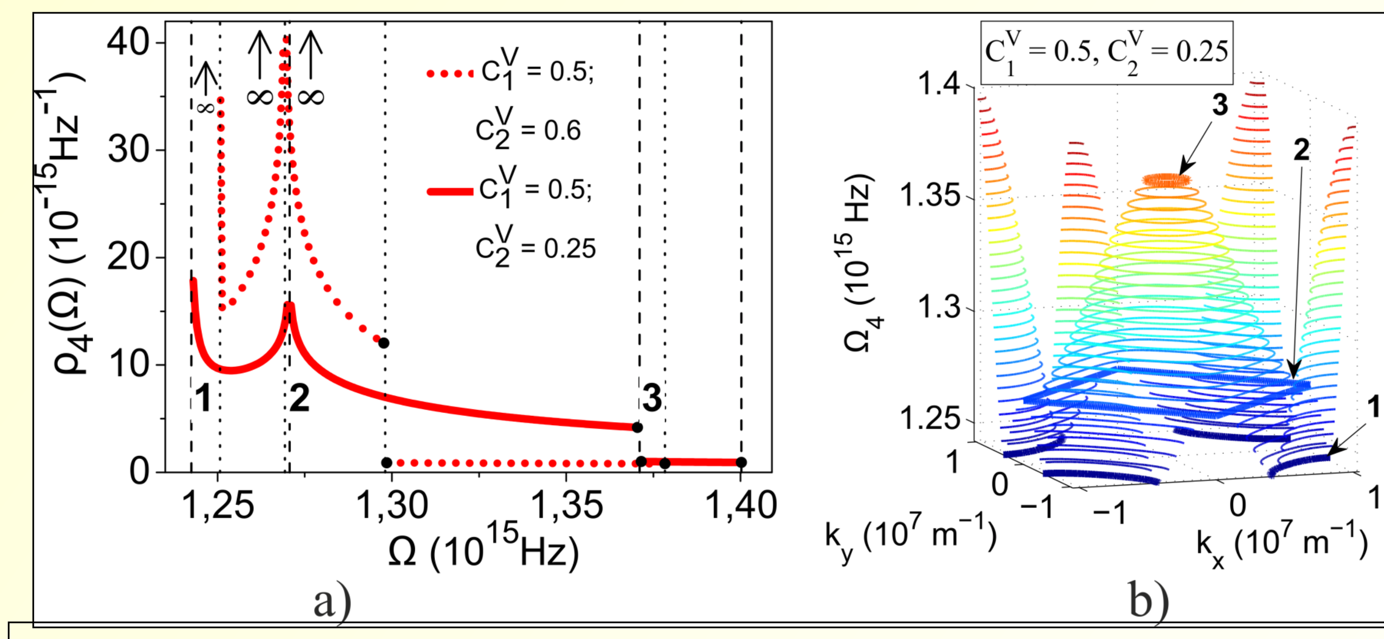
Dispersion plots of electromagnetic excitations in a polaritonic crystal for the values of vacancy concentrations C_1^V, C_2^V: a) 0,2 and 0,5 b) 0,6 and 0,5 ; c) 0,5 and 0,6; d) 0,5 and 0,25. Arrows in e) and f) point at the narrowed "bottle necks" (as compared to d) caused by alteration of the interaction parameters of the atomic and resonator subsystems.



Densities of polaritonic states evaluated for the four dispersion branches of an ideal crystal in the absence of vacancies.



Four dispersion branches (surfaces) of electromagnetic excitations in an ideal polaritonic crystal in the absence of vacancies.



Density of polaritonic states (a) in the fourth (upper) dispersion branch calculated for two different vacancy concentrations and the equifrequuency lines (b) of the fourth dispersion branch corresponding to the solid curve in Fig. (a). Numbers 1, 2, 3 indicate contours, which are responsible for the corresponding peculiarities of the density of states in Fig. (a).

Hamiltonian of the crystal $\hat{H} = \hat{H}_{at} + \hat{H}_{ph} + \hat{H}_{int}$

$$\hat{H}_{at} = \sum_{n,f} \varepsilon_{nf}^{at} \hat{b}_{nf}^{+} \hat{b}_{nf} + \frac{1}{2} \sum_{n \neq m} \sum_{f,g} \sum_{h,l} \hat{b}_{nf}^{+} \hat{b}_{ng}^{+} \left\langle \varphi_{nf}^{at} \varphi_{ng}^{at} \right| V_{nm} \left| \varphi_{nh}^{at} \varphi_{nl}^{at} \right\rangle \hat{b}_{nh} \hat{b}_{nl}$$

$$\hat{H}_{ph} = \sum_{n,\mu} \varepsilon_{n\mu}^{ph} \hat{\phi}_{n\mu}^{+} \hat{\phi}_{n\mu} - \frac{1}{2} \sum_{n \neq m} \sum_{\mu,\nu} \sum_{\lambda,\rho} \hat{\phi}_{n\mu}^{+} \hat{\phi}_{n\nu}^{+} \left\langle \varphi_{n\mu}^{ph} \varphi_{n\nu}^{ph} \right| A_{nm} \left| \varphi_{n\lambda}^{ph} \varphi_{n\rho}^{ph} \right\rangle \hat{\phi}_{n\lambda} \hat{\phi}_{n\rho}$$

$$\hat{H}_{int} = \sum_{n,f,g} \sum_{\mu,\nu} \hat{b}_{ng}^{+} \phi_{n\mu}^{+} \left\langle \varphi_{ng}^{at} \varphi_{n\mu}^{ph} \right| \hat{G}_n \left| \varphi_{nf}^{at} \varphi_{n\nu}^{ph} \right\rangle \hat{b}_{nf} \hat{\phi}_{n\nu}$$

Effective mass of polaritons:

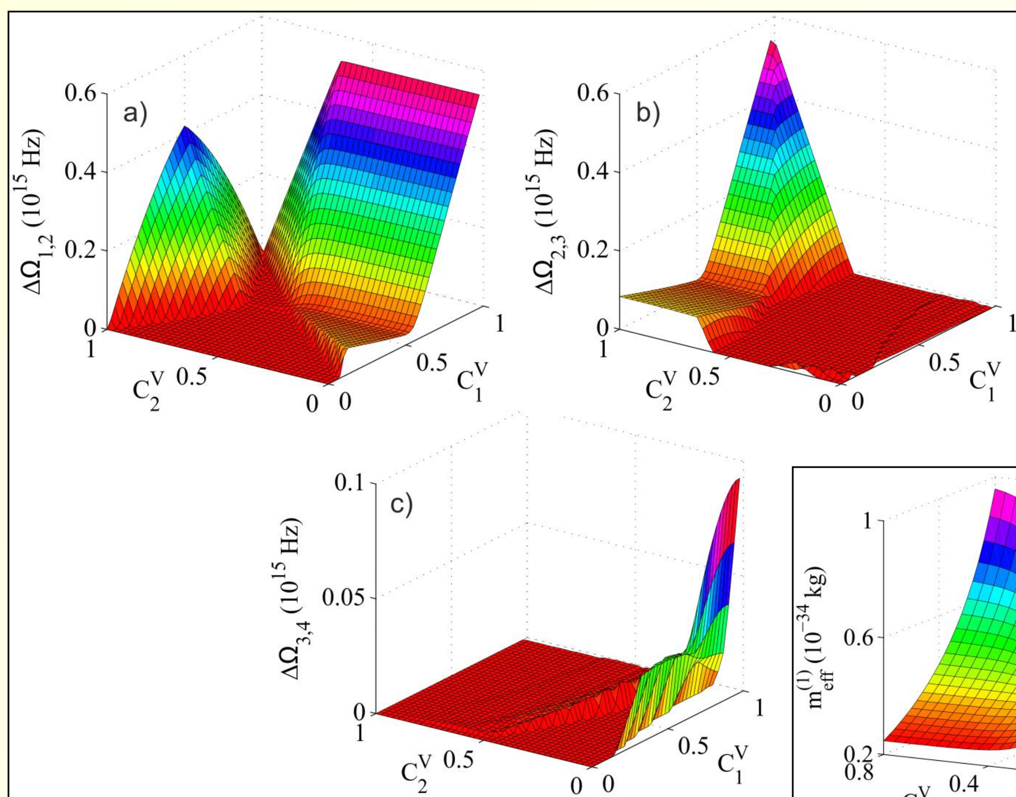
$$m_{1,2,3,4}^{(eff)}\left(k,\{C^{\nu}\}\right) = \hbar \left(\left. \frac{\partial^2 \Omega_{1,2,3,4}\left(k,\{C^{\nu}\}\right)}{\partial k^2} \right|_{k=0} \right)^{-1}$$

Density of states of polaritons :

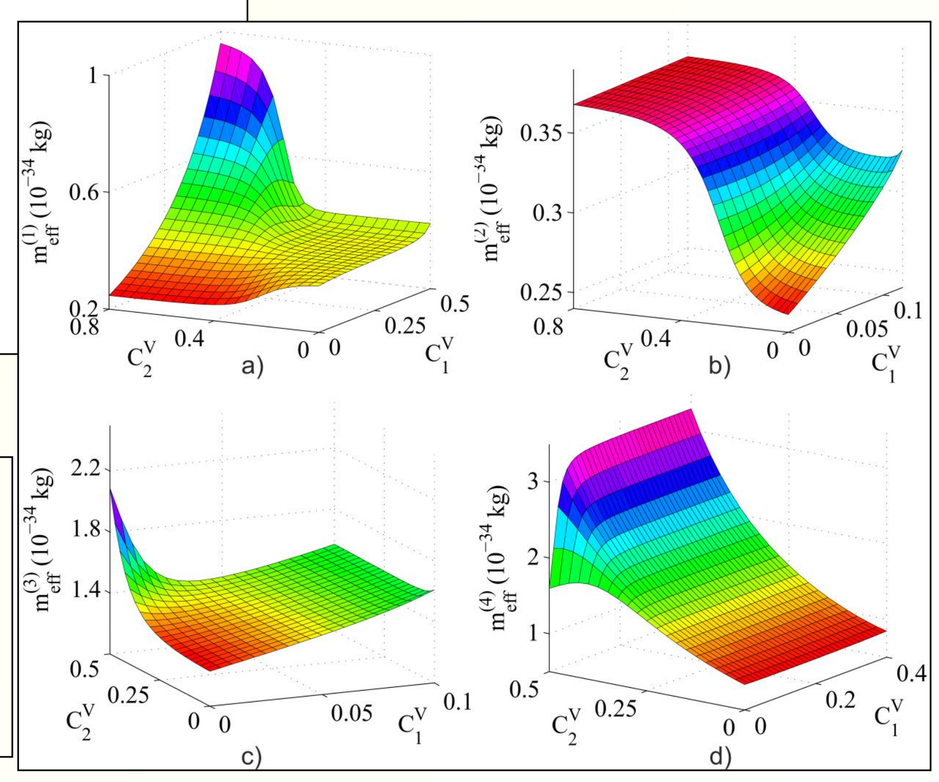
$$g_{\nu}\left(\Omega, C_1^V, C_2^V\right) = \left(\frac{d}{2\pi}\right)^2 \oint_{\Omega_\nu(\mathbf{k})=\Omega} \frac{dl}{\left|\nabla_{\mathbf{k}} \Omega_\nu(\mathbf{k})\right|}$$

$$\begin{Vmatrix} \hbar\left\langle \omega_{\mathbf{n}1}^{at} \right\rangle + V_{11}^{(a)}(\mathbf{k}) - \hbar\Omega & V_{12}^{(a)}(\mathbf{k}) & \left\langle g_{\mathbf{n}1} \right\rangle & 0 \\ V_{21}^{(a)}(\mathbf{k}) & \hbar\left\langle \omega_{\mathbf{n}2}^{at} \right\rangle + V_{22}^{(a)}(\mathbf{k}) - \hbar\Omega & 0 & \left\langle g_{\mathbf{n}2} \right\rangle \\ \left\langle g_{\mathbf{n}1} \right\rangle & 0 & \hbar\left\langle \omega_{\mathbf{n}1}^{ph} \right\rangle - A_{11}(\mathbf{k}) - \hbar\Omega & -A_{12}(\mathbf{k}) \\ 0 & \left\langle g_{\mathbf{n}2} \right\rangle & -A_{21}(\mathbf{k}) & \hbar\left\langle \omega_{\mathbf{n}2}^{ph} \right\rangle - A_{22}(\mathbf{k}) - \hbar\Omega \end{Vmatrix} = 0$$

$A_{11}(\mathbf{k}) \approx 2A_{11}(d)\left(\cos k_x d + \cos k_y d\right)$, $A_{22}(\mathbf{k}) \approx 2A_{22}(d)\left(\cos k_x d + \cos k_y d\right)\left(1-C_1^V\right)^2$, $A_{12}(\mathbf{k}) \approx A_{12}(0)\left(1-C_1^V\right)\exp(-i\mathbf{k}\cdot\mathbf{a})$, $A_{21}(\mathbf{k}) \approx A_{21}(\mathbf{k})$,
$V_{11}(\mathbf{k}) \approx 2V_{11}(d)\left(1-C_1^V\right)^2\left(\cos k_x d + \cos k_y d\right)$, $V_{22}(\mathbf{k}) \approx 2V_{22}(d)\left(1-C_2^V\right)^2\left(\cos k_x d + \cos k_y d\right)$, $V_{12}(\mathbf{k}) \approx V_{12}(0)\left(1-C_1^V\right)\left(1-C_2^V\right)\exp(-i\mathbf{k}\cdot\mathbf{a})$,
$V_{21}(\mathbf{k}) \approx V_{21}(0)\left(1-C_1^V\right)\left(1-C_2^V\right)\exp(i\mathbf{k}\cdot\mathbf{a})$.



Band gap widths between the three pairs of dispersion surfaces plotted as functions of vacancy concentrations in the atomic and resonator subsystems.



Effective masses of polaritons in the four dispersion branches constructed as functions of vacancy concentrations in the atomic and resonator subsystems.

Results

1. The presence of point-like defects in the studied polaritonic crystal results in a considerable transformation of its energy structure and optical properties as well as in renormalization of its polaritonic spectrum.
2. The presence of point-like defects leads to an increase of the effective mass of polaritons and hence to a decrease of their group velocity (as compared to an ideal defect-free polaritonic crystal).
3. The comparatively simple model of polaritonic crystal permits to employ the virtual crystal approximation. The study of polaritonic spectrum in more complex system requires the use more sophisticated approaches such as the one- ore multinode coherent potential method as well as the averaged T-matrix method and their various modifications.

References

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2. V.V. Rumyantsev , S.A. Fedorov, K.V. Gumennyk, M.V. Sychanova, Physica B. **461 (**2015) 32-37.
3. V.V. Rumyantsev, S.A. Fedorov, K.V. Gumennyk , M.V. Sychanova, A.V. Kavokin, Superlattices and Microstructures. **89 (**2016) 409-418.