Modelling a novel terahertz sensing scheme based on a black phosphorus-liquid crystal-DBR Tamm structure

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Abstract: Much attention has been drawn to devices that use a thin layer of black phosphorus (BP) and a distributed Bragg reflector (DBR) [1-2], e.g. for the purposes of sensing of biological materials in terahertz (THz) spectral region due to the absence of ionization damage to biological molecules. This study examines the possibility of controlling the spectral characteristics of the device using an additional liquid crystal layer in the Bragg mirror.

In this study we investigate the light propagation in a multilayer photonic structure which consist of a monolayer black phosphorus (BP), a defect layer (Si), a liquid crystal cell and a distributed Bragg reflector (Si, SiO_2). The structure of system is shown in Figure 1.

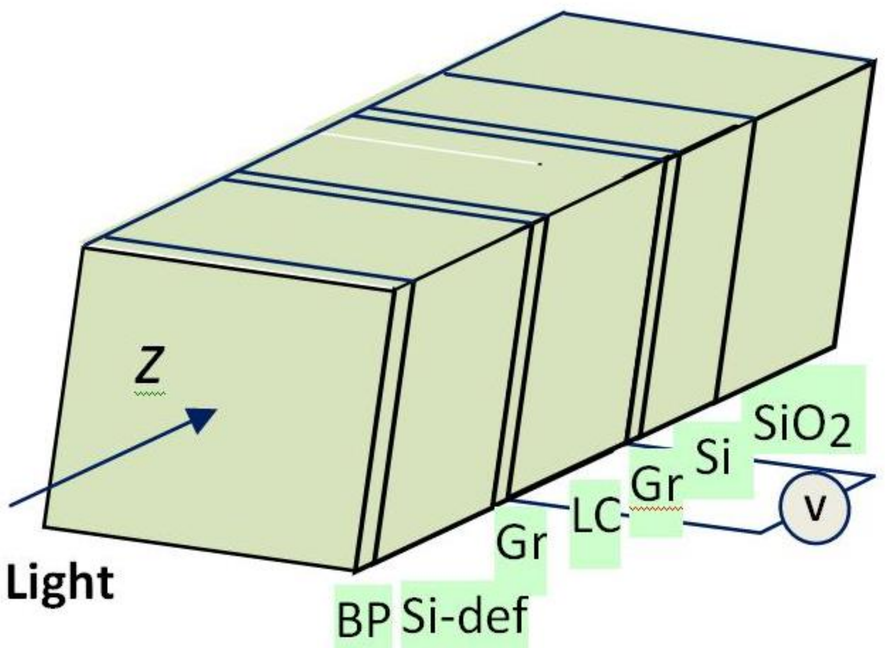

Fig.1. Schematic diagram of a system under study. Si-def is a defect layer which can tune a resonance dip in a reflectance spectrum. A bias DC voltage is applied to liquid crystal (LC) layer (BL037 LC) to control the orientation of LC molecules by reorienting them from planar to homeotropic state. It is shown only one pair of alternating layers of DBR.

In our numerical experiments we use a transfer matrix method [1] to study reflection spectra of the photonic structure shown in Figure 1. It can be shown that the field at z_l in layer l is related to the field at z_{l+1} in layer l+1 by a 2x2 transfer matrix T. The transfer matrix is given by $T(z_l, z_{l+1}) = D_{l\to l+1}P_{l,l+1}(\Delta z_l)$, where $\Delta z_l = z_{l+1} - z_l$ is the distance from z_l to z_{l+1} to the interface between layers l and l+1. The transmission and propagation matrices are given by

$$D_{l,l+1} = \frac{1}{2}\begin{pmatrix} 1+\left(k_{l+1}/k_l\right)+\frac{\sigma\mu_0\omega}{k_l} & 1-\left(k_{l+1}/k_l\right)+\sigma\frac{\mu_0\omega}{k_l} \\ 1-\left(k_{l+1}/k_l\right)-\frac{\sigma\mu_0\omega}{k_l} & 1+\left(k_{l+1}/k_l\right)-\sigma\frac{\mu_0\omega}{k_l} \end{pmatrix} \quad \text{and} \quad P_l\left(\Delta z\right) = \begin{pmatrix} e^{-ik_l\Delta z} & 0 \\ 0 & e^{+ik_l\Delta z} \end{pmatrix}$$

, σ is electrical conductivity of anisotropic semiconductor BP or quasi-metallic graphene, μ_0 is the vacuum permeability. k_l is the wave number in the l-th layer of the photonic structure ($k_l = (\omega/c)\sqrt{\varepsilon_l}$), ε_0 and c are the dielectric constant and speed of light in vacuum. Signs in front of σ allow for polarization *s* and *p* before electrical conductivity in the expression for $D_{l,l+1}$. Black phosphorus (BP) is anisotropic material, and it has different values of electrical conductivity in the *xx* and *yy* directions. Transmission matrix connects the fields on one side of structure to those on other side of structure; propagation matrix relates electric fields propagating over a distance in a homogeneous medium. Fresnel reflection coefficients *R* are found from the matrix of products of pairs of matrices *D* and *P*. **Figures** 2-4 show the results of numerical simulation of the system under consideration with the parameters:

$\varepsilon_{Si}=3.42^2$, $\varepsilon_{SiO2}=1.9^2$, $\varepsilon_{Gr}=90^2$[2], $d_{Si}=25\mu$m, $d_{SiO2}=81\mu$m, $d_{Def}=75\mu$m, $d_{LC}=100\mu$m [3], $n_{el} = 5\times10^{17}$ m^{-2} (BP electron concentration). **Fig. 2** illustrates the dependence of the dielectric function of the LC on the tilt angle of its director. Figures **3** and **4** illustrate the change in spectrum with a change in the tilt angle of the LC director. It can be seen that the spectrum is shifted to the right by 4.5 μm ($\Delta n_{LC} = n_e - n_o = 0.32$).

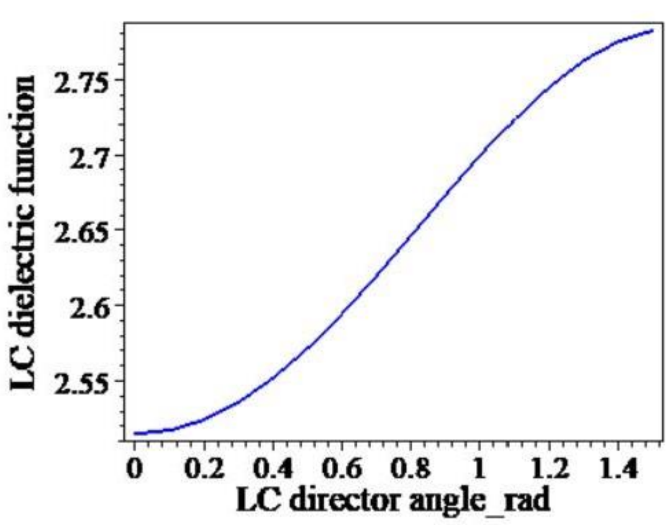

Fig.2

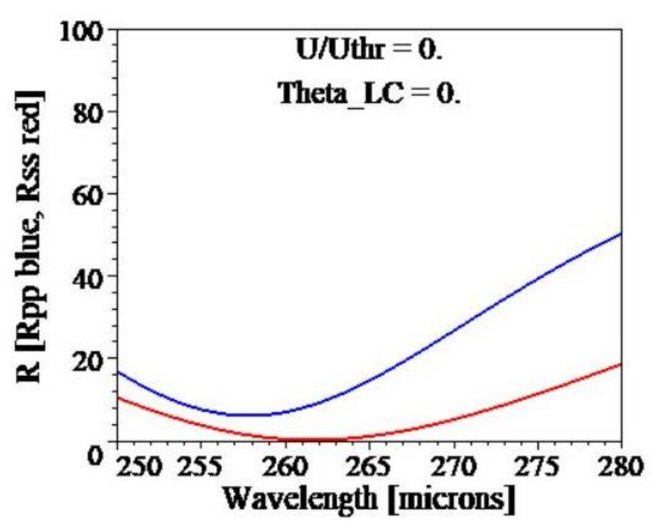

Fig.3

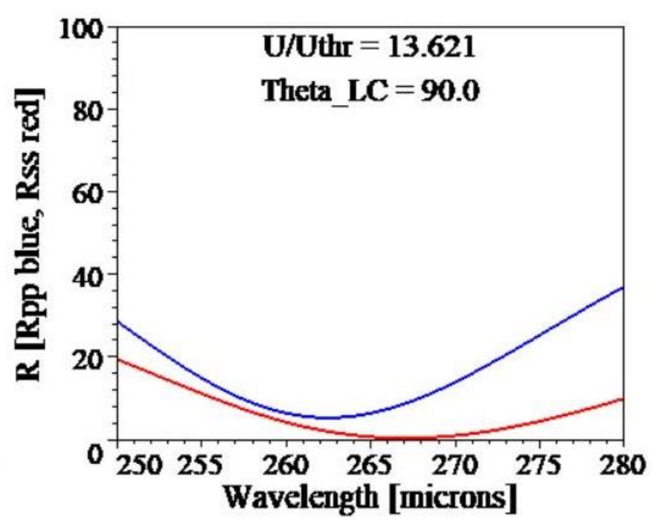

Fig.4

Significantly a broader tune range of spectrum can be achieved by using for example high birefringence in the THz band liquid crystal mixtures and compounds.

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