Iodine Plasmonic Crystal as the Visible-Range Spectral Filter

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Abstract. We analyse the optical properties of the new hyperbolic metamaterial based on the one-dimensional mesoporous aluminum oxide (Al₂O₃) photonic crystal film doped by metallic iodine (I₂) nanoparticles. The nanocomposite is a metal-dielectric hybrid and combines the classical photonic crystal features (such as photonic bandgaps, light deceleration, negative refraction etc.) with the metallic ones (low-frequency mirroring, plasmons etc.). To get this, we propose to saturate the pores (microcavities) of the periodic aluminum oxide photonic crystal matrix synthesized by the controlled acid etching at its anionization, by the iodine vapor. This way, in the photonic crystal pores, we form the cold plasma of the iodine free electrons, and make the nanocomposite the plasmonic photonic one. Note, that the iodine saturation level defines the plasma frequency which is directly affects the crystal characteristics, so we get them easy-tunable. For example, we offer the two iodine-saturated photonic crystals with various doping level in the pass-and-reflect scheme to spectral filter the optical radiation. At last, we also wish to note that simplicity of the saturation technology makes the iodine plasmonic crystals attractive for the wide commercial usage in the large-scale optic and photonic applications and devices (such as spectral filters, optical amplifiers, high-performance selective mirrors, photonic sensors etc.).

1. Introduction
Nowadays, there is a worldwide interest to the new photonic materials. The photonic crystals – nanocomposites with the photonic bandgap at the visible spectral region – are the most prominent of them due to their unique features, such as the negative refraction, the light deceleration etc. [1]

The simplest photonic crystal is the 1D Bragg stack of the identical material layers with the regular gaps between [2]. In the case of metal layers, the metal free electrons in layers form the cold plasma, and the photonic crystal becomes the plasmonic one. Therefore, we get a new metamaterial to be investigated.

2. Analysis
To deal with the plasmonic crystal, we use the Bloch-Floquet formalism [3,4]. This way, the electromagnetic waves in the 1D periodic medium describes by the dispersion equation [5]:

\[
cos k a = \cos k_1 a_1 \cdot \cos k_2 a_2 - \frac{1}{2} \left( \frac{n_1}{n_2} + \frac{n_2}{n_1} \right) \cdot \sin k_1 a_1 \cdot \sin k_2 a_2.
\]

(1)

Here \( a_1 \) and \( a_2 \) are, respectively, the odd and the even layers’ thicknesses, \( n_1 \) and \( n_2 \) are its’ refractive indices, \( k_i = \omega \cdot n_i / c \) (\( i = 1,2 \)) are the wavenumbers, \( \omega \) is the wavefrequency and \( c = 3 \cdot 10^8 \) m/s is the speed of light.
In the plasmonic crystal, there are the metallic \((i = 1)\) layers and the dielectric \((i = 2)\) ones in-between.

For the metallic layer, we have the cold electron plasma with the refractive index [6]

\[
n_1 = \sqrt{1 - \frac{\omega_p^2}{\omega^2}},
\]

where \(\omega_p = q e \cdot \left(\frac{n_e}{m e} \epsilon_0\right)^{1/2}\) is the plasma frequency, \(q e = 1.6 \cdot 10^{-19} \text{C}\) is the elementary charge, \(m e = 9.1 \cdot 10^{-31} \text{kg}\) is the electron mass, \(\epsilon_0 = 8.85 \cdot 10^{-12} \text{F/m}\) is the electric constant and \(n_e\) is the electron concentration. And because of metal, \(n_e = n_0 \cdot v\), where \(n_0\) is the atom concentration and \(v\) is the metal’s chemical valence. For example, for the crystalline iodine \(I_2\) [7] \(n_0 = N/V = 2/(325 \cdot 10^{-30}) = 6.2 \cdot 10^{27} \text{m}^{-3}\), \(v = 2\) and, therefore, \(\omega_p = 6 \cdot 10^{15} \text{rad/s}\). So, the typical \(\omega_p\) is about \(10^{15} \text{rad/s}\), and the plasmons are the optical ones.

As for the dielectric layers, their refractive index

\[
n_2 = \text{const}
\]

is the index of refraction of the corresponding material and can varies from \(n_2 = 1\) (void) to almost infinity (organic polymers).

Anyway, the composite reflection (at the normal incidence) is [8]

\[
R(\omega) = \left|\frac{n(\omega)-1}{n(\omega)+1}\right|^2 = \left|\frac{k(\omega)-\omega/c}{k(\omega)+\omega/c}\right|^2,
\]

the group velocity of light in the composite is

\[
v(\omega) = \frac{d\omega}{dk} = \left[\frac{dk(\omega)}{d\omega}\right]^{-1},
\]

and the effective refractive index is

\[
n(\omega) = \frac{c \cdot k(\omega)}{\omega} \cdot \text{sign} \, v(\omega)
\]

with \(k(\omega)\) is defined by (1).

3. Simulation

The simulation results for the iodine-sapphire plasmonic crystal are presented at the fig. 1-4. The crystal parameters are \(a_1 = a_2 = 100 \text{ nm}, \omega_p = 6 \cdot 10^{15} \text{rad/s (iodine)}\) and \(n_2 = 1.77\) (sapphire).

**Figure 1.** The dispersion law (1) for the electromagnetic waves in the iodine-sapphire plasmonic crystal. Note the low-frequency (zero to \(\omega_p\)) bandgap due to plasmons.
**Figure 2.** The reflectance (4) of the plasmonic crystal. In the visible range, there are several 100%-reflectance bands due to the photonic bandgaps. The widest low-frequency band is the plasmonic one.

**Figure 3.** The group velocity (5) of light in the plasmonic crystal. No-solution areas are photonic bandgaps. Note the light deceleration to the zero at the bandgap edges.

**Figure 4.** The effective refractive index of the nanocomposite. Due to plasmons $|n| < 1$ (see (2)).
4. Discussion

The simulation gives (see fig. 1) that in the plasmonic crystal, the acoustic mode cuts itself at the plasma frequency. This forms the additional low frequency (zero to the plasma frequency) photonic bandgap to reflect the light (fig. 2). This way, two plasmonic crystals with different plasma frequencies can act as a spectral filter, fig. 5.

At the fig. 5, one can see, that when the crystal no. 2 are rotated at the small angle (for the convenience, at the fig. 5 the angle is exaggerated), we have the pass-and-reflect scheme to filter the electromagnetic radiation. For example, when the crystal no. 1 plasma frequency is \( \omega_p = 2.4 \times 10^{15} \text{ rad/s} \) (\( \lambda = 800 \text{ nm} \)) and the crystal no. 2’s one is \( \omega_p = 4.7 \times 10^{15} \text{ rad/s} \) (\( \lambda = 400 \text{ nm} \)), we get the visible range filtered at whole.

**Figure 5.** Two plasmonic crystals (at the fig., no. 1 and no. 2) act as a spectral filter.

Note, that the plasmonic crystal’s plasma frequency can be tuned by the doping of crystal’s metallic layers by the dielectric inclusions. This dilutes the metal concentration and lessen the plasma frequency. To do this, we propose the inverse technique: to saturate the pores of layer-forming dielectric matrix by the iodine vapor (our experiments [9,10] show that solid metals are hard to enter), to create the “metallic” layers. This way, the mesoporous aluminum-based photonic crystal films [11-17] are the best to deal with, because of its porous structure, fig. 6.

**Figure 6.** The SEM image of Al\(_2\)O\(_3\) photonic crystal film: (a) slice with horizontal layer periodicity, (b) top view with a lot of pores of 10 nm in a diameter and 100 nm in a length (from our paper [16]).
5. Conclusion
The results show that the iodine-saturated mesoporous aluminium-based photonic crystal is the new hyperbolic (see (2)) metamaterial, the plasmonic photonic crystal, combines the photonic crystal (specific dispersion, fig. 1; photonic bandgaps, fig. 2; slow light, fig. 3; negative refraction, fig. 4) and metal (low-frequency mirroring) features. This makes it perspective for the various photonic applications (such as the electromagnetic field amplifiers, e.g. for the enhancement of the Raman scattering [17]; high-efficiency selective mirrors, photonic sensors, etc.) and, besides, for the spectral filtering of an optical radiation. Moreover, the simplicity of technology (vapour saturation of the dielectric matrix) makes it attractive for the wide commercial usage.

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