RESONANCES IN A CHAIN OF BIMETALLIC NANOPARTICLES ON A DIELECTRIC SUBSTRATE

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Abstract

Chains of plasmonic nanoparticles are currently being actively studied with a view to their use as a possible design for optical radiation waveguides. This application is associated with the propagation of plasmons in them with a transverse localization size significantly smaller than the wavelength of light. The scientific literature has already described studies of chains of monometallic nanoparticles of various shapes (spherical, prolate and oblate spheroids) [1]. One of the most important parameters of such systems is the frequency of the collective (chain) resonance. It is known that in the case of isolated nanoparticles, bimetallic nanoparticles are more effective in terms of plasmon resonance regulation due to the additional ability to change the core size and shell thickness [2]. Therefore, we should expect an expansion of such capabilities for controlling collective resonances in chains of bimetallic nanoparticles.

Statement of the problem and results of calculations

Let the chain under study be located on a dielectric substrate with permittivity ϵ_{d} in a medium with permittivity ϵ_{m}. The transverse component of the polarizability tensor of the chain under consideration is determined by the relation

$$\alpha_{\perp}^{\mathrm{chain}} = \frac{\alpha_{@}(\omega)}{1-\frac{\alpha_{@}(\omega)}{d^{3}\epsilon_{\mathrm{m}}}\left(\mathcal{S}_{\perp}^{d}+\frac{\epsilon_{\mathrm{d}}-\epsilon_{\mathrm{m}}}{\epsilon_{\mathrm{d}}+\epsilon_{\mathrm{m}}}\mathcal{S}_{\perp}^{i}\right)} \qquad (1)$$

where d is the distance between particles in the chain; $S_{\perp}^{d}$ and $S_{\perp}^{i}$ are chain sums describing the interaction between particles in the chain and the interaction with the image dipoles; $a_{@}$ is the polarizability of an isolated bimetallic nanoparticle.

The condition for collective resonance in the nondissipative approximation is that the denominator of expression (1) equals zero, from which, for the resonance frequencies ω_{res}, we obtain a biquadratic equation with two positive roots and two negative roots, the latter having no physical meaning:

$$a\omega^{4}+b\omega^{2}+c=0 \qquad (2)$$

where:

$$a=(1-\mathcal{A}_{\perp})\epsilon_{\mathrm{s}}^{\infty}\left[2\epsilon_{\mathrm{s}}^{\infty}(1-\beta_{\mathrm{c}})+\epsilon_{\mathrm{c}}^{\infty}(1+2\beta_{\mathrm{c}})\right]+ +(2+\mathcal{A}_{\perp})\epsilon_{\mathrm{m}}\left[\epsilon_{\mathrm{c}}^{\infty}(1-\beta_{\mathrm{c}})+\epsilon_{\mathrm{s}}^{\infty}(2+\beta_{\mathrm{c}})\right] \qquad (3)$$

$$b=-(1-\mathcal{A}_{\perp})\left[4\epsilon_{\mathrm{s}}^{\infty}(1-\beta_{\mathrm{c}})\omega_{p,\mathrm{s}}^{2}+(1+2\beta_{\mathrm{c}})\left(\epsilon_{\mathrm{s}}^{\infty}\omega_{p,\mathrm{c}}^{2}+\epsilon_{\mathrm{c}}^{\infty}\omega_{p,\mathrm{s}}^{2}\right)\right]- -(2+\mathcal{A}_{\perp})\epsilon_{\mathrm{m}}\left[(1-\beta_{\mathrm{c}})\omega_{p,\mathrm{c}}^{2}+(2+\beta_{\mathrm{c}})\omega_{p,\mathrm{s}}^{2}\right]; \qquad (4)$$

$$c=(1-\mathcal{A}_{\perp})\omega_{p,\mathrm{s}}^{2}\left[2(1-\beta_{\mathrm{c}})\omega_{p,\mathrm{s}}^{2}+(1+2\beta_{\mathrm{c}})\omega_{p,\mathrm{c}}^{2}\right] \qquad (5)$$

and:

$$\beta_{\mathrm{c}}=\left(\frac{R_{\mathrm{c}}}{R}\right)^{3} \qquad \mathcal{A}_{\perp}=\frac{R^{3}}{\epsilon_{\mathrm{m}}d^{3}}\left(\mathcal{S}_{\perp}^{d}+\frac{\epsilon_{\mathrm{d}}-\epsilon_{\mathrm{m}}}{\epsilon_{\mathrm{d}}+\epsilon_{\mathrm{m}}}\mathcal{S}_{\perp}^{i}\right) \qquad (6)$$

The real roots correspond to the frequencies of collective (chain) resonances, which are determined by the material properties of the nanoparticles, the substrate and the surrounding medium, the interparticle spacing in the chain, and the core and shell dimensions of the particles.

The calculated results for the chain resonance frequencies of Au@Ag and Ag@Au particle chains at different values of β_{c} are presented in Table 1.

Table 1

β_{c}	Au@Ag		Ag@Au	
	$\hbar\omega_{\mathrm{res}}^{(1)}$, eV	$\hbar\omega_{\mathrm{res}}^{(2)}$, eV	$\hbar\omega_{\mathrm{res}}^{(1)}$, eV	$\hbar\omega_{\mathrm{res}}^{(2)}$, eV
0.037	0.037	3.015	1.505	2.588
0.072	0.072	3.045	1.498	2.572
0.125	0.125	3.089	1.488	2.548
0.198	0.198	3.151	1.474	2.514
0.296	0.296	3.235	1.457	2.468
0.422	0.422	3.347	1.436	2.409
0.579	0.579	3.492	1.412	2.331
0.770	0.770	3.679	1.385	2.229

Conclusions

It should be noted that the behaviour of the chain resonance frequency splitting $\Delta\omega_{\mathrm{res}}=\omega_{\mathrm{res}}^{(1)}-\omega_{\mathrm{res}}^{(2)}$ is fundamentally different for particles with different morphologies. In the case of Au@Ag particle chains, an increase in β_{c} (the core metal content in the particle) leads to an increase in $\Delta\omega_{\mathrm{res}}$ – the chain resonances "repel" each other. In contrast, for Ag@Au chains, $\Delta\omega_{\mathrm{res}}$ decreases – the chain resonances "attract" each other.

References

[1] M. S. Maniuk, A. V. Korotun, V. P. Kurbatsky. Low Temp. Phys., 51 (2025) 156.