Plasmonic Properties of Selfsimilar Cluster of Silver Nanowires

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***Abstract*—We investigate the plasmonic properties of selfsimilar linear cluster of silver nanowires and compare the obtained results with the characteristics of standard (or identical) coupled nanowires. We came to the conclusion that such a structural complexity of cluster is able to provide significant increase in the concentration of the local field in the gap between the smallest nanowires. Optimized forms of clusters with narrowband and high-intensity plasmonic resonances are revealed.**

Keywords— selfsimilar cluster; plasmon resonances; localized surface plasmons

I. INTRODUCTION

Currently plasmonic properties of metal nanowires are a hot topic in the field of nanoplasmonics [1]. Localized surface plasmons (SPs) appear due to the collective oscillations of conduction electrons excited by the external electromagnetic field at the boundary between the metal and the dielectric environment. Typically the metals that demonstrate such plasmonic property are silver [2], gold [3], platinum [4], and others.

Their plasmonic resonances are extremely dependent on the wavelength of the excitation and cause the spatially concentrated enhancement of field. These localized confined domains are called hot spots. Localized and delocalized SPs have a large field of applications (e.g. nanobiosensors [5, 6], nanolasers [2,7], nanoantennas [8], and spectroscopy [9]). Hot spots were investigated near superconducting current-carrying nanowires [10], twisted nanowire plasmonic oscillators [11], and silver nanowire dimers [12]. Properties of SPs are very sensitive to changes in surrounding dielectric environment [13, 14] and this opens a possibility for optical sensing applications [15].

There is increasing interest to using the plasmon properties of silver nanoparticles in various sensors and other nanodevices [16]. Silver nanoobjects are very efficient at absorbing and scattering the light and, in contrast to many colorants, have a color (i.e. the SP resonance wavelength) that depends on the shape and, to lesser extent, on the size of the nanoparticle.

Important problem of nanoplasmonics is the creation of devices that can concentrate optical field in nanometer domain. Typical lenses can focus the field only in a spot of the order of the wavelength. In the gaps between nanoobjects and in antisymmetric plasmonic nanoshells it is possible to increase the local concentration of field by a factor of 10-100.

For greater concentration of optical fields, some groups had proposed to investigate selfsimilar clusters consisting of silver nanospheres [17]. This allowed scientists to create effective nanolenses demonstrating hot spots with giant field enhancements. Other groups used selfsimilar gold nanoparticle for a cascaded enhancement of the field [18]. In paper [19], researchers studied the local field enhancement properties of self-similar nanolenses and their results were comparable with the performance of standard dimer nanoantennas.

II. STATEMENT OF THE PROBLEM AND METHOD OF SOLUTION

From the fundamental and practical aspects, the interest and importance of the plasmonic properties of nanoobject clusters are due to the fact that in clusters, in contrast to individual nanoobjects, there are at least two dimension parameters: the size of nanoobjects and the separation distances between them. As we know from papers [14, 20], the plasmon properties of isolated nanoobject are complicated. It is natural to expect that the properties of plasmon oscillations in nanoclusters will be even more complicated. This raises the question of how plasmon properties of a cluster of two or more nanoobjects are related to plasmon properties of an isolated nanoelement.

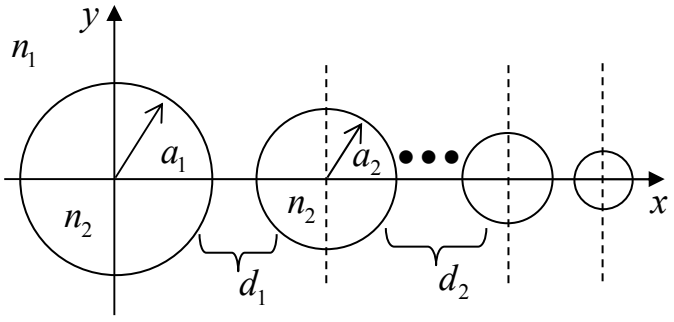

Fig. 1. Schematic view of the investigated structure: a finite linear cluster of N selfsimilar nanowires.

In our paper, we consider a finite linear cluster of several silver nanowires with progressively decreasing (or increasing) radii and separation distances between them (see schematic view of the cross-section geometry in Fig. 1). In computations,

we assume that the radius of each nanowire is $a_1, a_2, ..., a_n$ and the separation distance between them is $d_1, d_2, ..., d_{n-1}$. The metal refractive index n_2 is interpolated from the original optical data for silver of [21]. We also assume that our structure is embedded into medium with index of refraction $n_1 = 1$ and that the time dependence is $e^{+i\omega t}$.

For analytical-numerical study of the scattering of light by the explained cluster of circular nanowires, we use the method of [22-26] noting that in our case the values of wire radii and distances between them are not the same. Still the main idea of research is to reduce the wave-diffraction problem to an infinite system of algebraic equations that can be solved with controlled accuracy. To characterize the fields, we introduce local polar coordinates with origins on the each wire axes. Then the solution is sought in the form of Fourier series,

$$H(\rho_m, \varphi_m) = \sum_{s=-\infty}^{+\infty} A_s^m J_s(k_m \rho_m) e^{is\varphi_m}, \quad (1)$$

$$H(\rho, \varphi) = \sum_{m=1}^{N} \sum_{s=-\infty}^{+\infty} \overline{A}_s^m H_s^{(2)}(k\rho_m) e^{is\varphi}, \quad (2)$$

Here $k = n_1 \cdot \omega_m \cdot c^{-1}$, $k_m = n_2 \cdot \omega_m \cdot c^{-1}$, $m = (1, ..., N)$, c is light velocity in vacuum, N is the number of nanowires in a linear cluster, global polar coordinates (ρ, φ) are associated with the Cartesian system (x, y). Equation (1) represents the field inside the m-th nanowire and equation (2) corresponds to the external scattered field.

The unknown coefficients A_s and $\overline{A}_s$ are calculated from the boundary conditions, which require the continuity of the tangential components of the total electric and magnetic fields at each surface. Applying the addition theorem for the Bessel functions, we derive an infinite system of algebraic equations that is cast to the Fredholm second-kind form and hence can be truncated to provide a controlled numerical accuracy.

III. Analysis and Results

Figure 2 presents the spectra of the scattering cross section (SCS) of a linear cluster of three selfsimilar (red line) and identical (blue line) silver nanowires. Direction of incidence of a plane wave is shown in the inset. Shift of peak resonance for the illumination (a) is observable from 344 nm (standard nanowires) to 353 nm (selfsimilar nanowires) and for the illumination (b) from 346 nm (standard nanowires) to 362 nm (selfsimilar nanowires). We see that the selfsimilar and standard nanowires display far-field enhancements of the same order of magnitude, however the wires with decreasing radii show slightly more intensive and red shifted resonance at about 360 nm. The shift in the resonance wavelength reaches a maximum when the separation distance between the nanowires is approximately equal to the wavelength. The concentrated field near the largest nanowire is enhanced. The local field of this nanowire excites the following nanowire.

For this smallest nanowire the contribution of excitation from the exciting field is negligible if compared to the excitation induced by the first bigger nanowire.

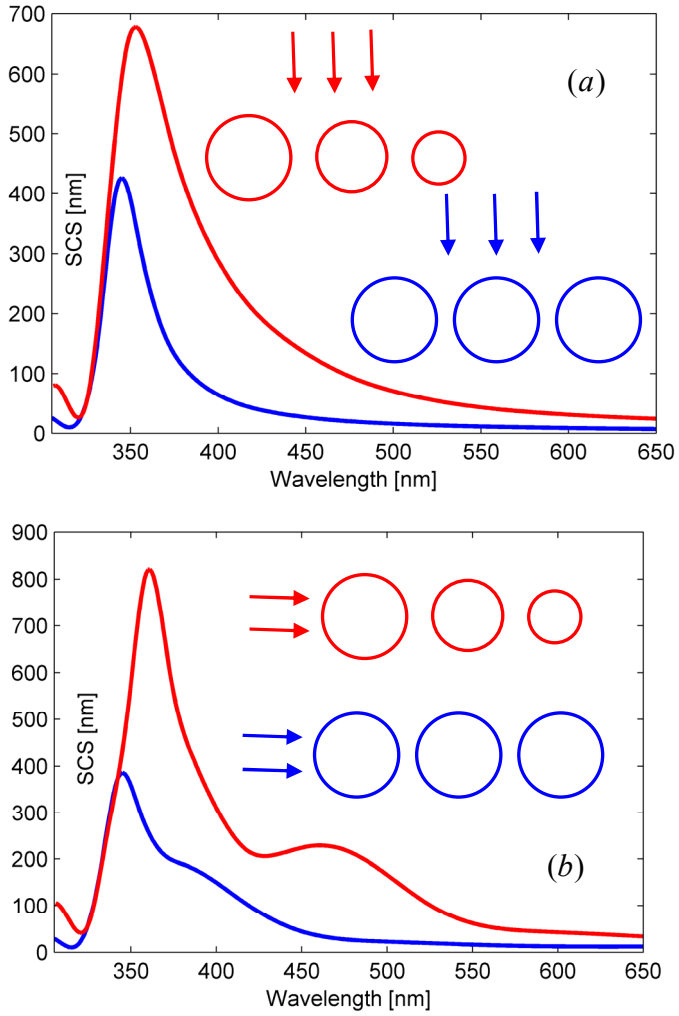

Fig. 2. SCS for a linear cluster consisting from three silver identical (blue line) or selfsimilar (red line) nanowires with separated distance between them $d_1 = d_2 = 350$ nm. For standard cluster radii are $a_1 = a_2 = a_3 = 35$ nm and for selfsimilar nanowires radii are $a_1 = 35$ nm, $a_2 = 30$ nm and $a_3 = 25$ nm. The direction of the plane wave is shown in the inset.

Figure 3 shows the SCS for three selfsimilar silver nanowires with different radii and the same separation distances, $d_1 = d_2 = 350$ nm. We investigate nanowires with the radii $a_1 = 60$ nm, $a_2 = 30$ nm, $a_3 = 15$ nm (blue line) or $a_1 = 35$ nm, $a_2 = 25$ nm, $a_3 = 15$ nm (black line) or $a_1 = 35$ nm, $a_2 = 30$ nm, $a_3 = 25$ nm (red line).

The decrease in the radius of nanowires is twice or by 10 nm or by 5 nm, respectively. We see that with increasing of change in radius of silver nanowires the amplitude of field increases. Nanowires with increase of change values for radius illustrate red shifted plasmonic resonance from 353 nm (red line) to 379 nm (blue line).

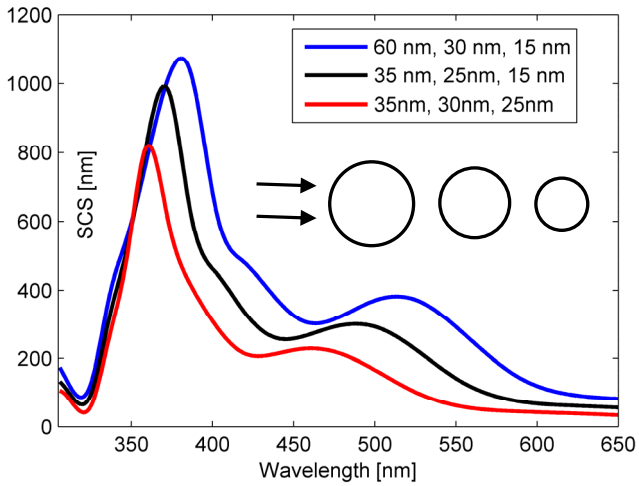

Fig. 3. SCS for three selfsimilar silver nanowires of a linear cluster with separated distance between them $d_1 = d_2 = 350$ nm and different radii: 1) for red line - $a_1 = 35$ nm, $a_2 = 30$ nm, $a_3 = 25$ nm; 2) for black line - $a_1 = 35$ nm, $a_2 = 25$ nm, $a_3 = 15$ nm; 3) for blue line - $a_1 = 60$ nm, $a_2 = 30$ nm, $a_3 = 15$ nm.

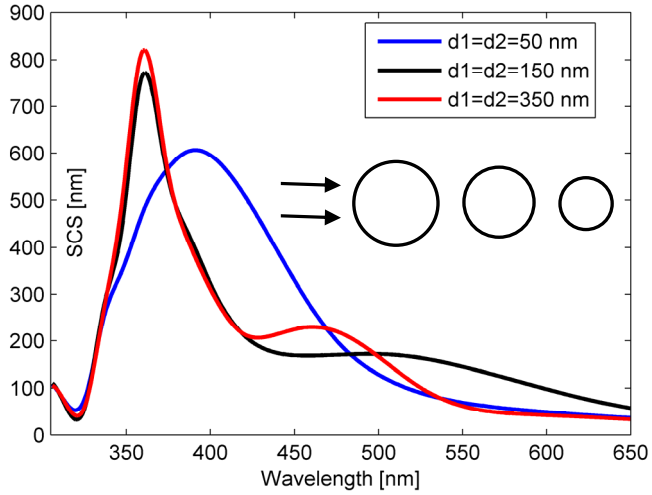

Fig. 4. SCS for three selfsimilar silver nanowires of a linear cluster with radii $a_1 = 35$ nm, $a_2 = 30$ nm, $a_3 = 25$ nm and different values of separation distance between nanowires: 1) for red line - $d_1 = d_2 = 350$ nm; 2) for black line - $d_1 = d_2 = 150$ nm; 3) for blue line - $d_1 = d_2 = 50$ nm.

Fig. 4 illustrates the SCS for three selfsimilar silver nanowires with different separation distances and for radii $a_1 = 35$ nm, $a_2 = 30$ nm, $a_3 = 25$ nm. We investigate the following values for separation: $d_1 = d_2 = 50$ nm (blue line) or $d_1 = d_2 = 150$ nm (black line) or $d_1 = d_2 = 350$ nm (red line). We see that with decreasing of separation distance between the selfsimilar silver nanowires the intensity of the plasmon resonance decreases. A cluster of selfsimilar nanowires of the same radius with increase of distance between them demonstrate blue shifted plasmon resonance from 384 nm (blue line) to 353 nm (red line).

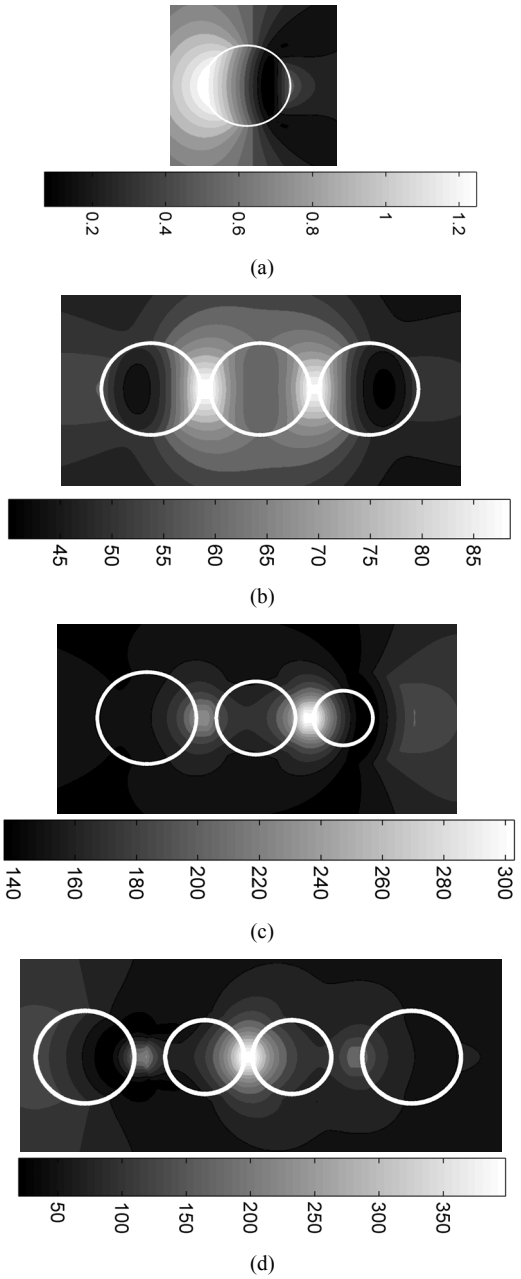

Fig. 5. The distribution of magnetic near-field for silver selfsimilar nanowires of a linear cluster for separation distance $d_{1,\ldots,n-1} = 5$ nm ($n_1 = 1$): (a) $a = 25$ nm, $\lambda = 344$ nm, (b) $a_1 = a_2 = a_3 = 25$ nm, $\lambda = 340.5$ nm, (c) $a_1 = 25$ nm, $a_2 = 20$ nm, $a_3 = 15$ nm, $\lambda = 342$ nm, (d) $a_1 = a_4 = 25$ nm, $a_2 = a_3 = 20$ nm, $\lambda = 343.5$ nm.

Localized SPs of a linear cluster of silver nanowires are the symmetric and antisymmetric forms of SPs of isolated nanowire. In the gap between two nanowires, it is possible to achieve spatially concentrated enhancement of field (hot spot). Fig. 5 shows the magnetic near-field pattern for three and four silver nanowires of a linear cluster with separation distance 5 nm. Fig. 5(a) presents the field pattern for an individual silver nanowire. We see that with increasing of silver nanowires number the concentration of the enhancement of field in the gap increases, and the maximal enhancement of these fields is

very sensitive to the form of investigated structure. In each case, we computed the pattern in SP resonance. The maximum of enhancement of local field between several standard (identical) nanowires was presented in [1] (see Fig. 5(b)).

The effect of smaller radius of nanowires is illustrated in Fig. 5(c). For this case, the maximum of field amplitude in the hot spot for selfsimilar nanowires is approximately 300 times larger than for isolated nanowire. We have also investigated centrally symmetric linear cluster of selfsimilar nanowires (see Fig. 5(d)). For this case, the hot spot appears in the gap between the smallest nanowires. In this figure it is clearly seen that between of the smallest nanowires the local field increases more than 317 times larger than for single wire.

Selfsimilarity is not a necessary condition for focusing and concentration of the field in the nanoscale domain, but it leads to a special effective formulation of the problem and its solution. In clusters of two or more selfsimilar nanowires plasmon resonances fields have complicated structure. In this case, plasmon fields strongly localized in the gaps do not actually feel the presence of other nanowires and therefore can exist almost independently in any structures. As a result all other plasmon fields lead to the excitation of the full cluster. At the initial time the excited field of single nanowire due to interactions will affect neighboring wires and field will spread throughout the cluster. That is the cluster will become a plasmon waveguide.

IV. CONCLUSIONS

The plasmonic properties of a selfsimilar linear cluster of silver nanowires have been investigated. Obtained characteristics have been compared with the results for identical silver nanowires. Selfsimilarity of nanowires leads to increased focusing and concentration of the field in the gaps between them. The effect of decreasing the radii of nanowires is maximal for centrally symmetric linear cluster of selfsimilar nanowires. The sensitivity of the field spectrum for silver selfsimilar cluster to changes of the radii of nanowires and the separation distances between them has been shown.

REFERENCES

[1] N. P. Stognii and N. K. Sakhnenko, “Accurate investigation of coupled plasmonic resonances in a chain of silver nanowires,” Proc. In. Conf. Math. Meth. Electr. Th. (MMET-2016), pp. 192-195, Lviv, Ukraine, July 5-7, 2016.

[2] D. M. Natarov, “Modes of a core-shell silver wire plasmonic nanolaser beyond the Drude formula,” J. Opt., vol. 16, no 7, pp. 075002/6, 2014.

[3] M. Wulf, A. de Hoogh, N. Rotenberg, and L. Kuipers, “Ultrafast plasmonics on gold nanowires: confinement, dispersion, and pulse propagation,” ACS Photonics, vol. 1, no 11, pp. 1173–1180, 2014.

[4] A. Balouch, A. A. Umar, S.T. Tan, S. Nafisah, S. K. M. Saad, M. M. Salleh, and M. Oyama, “Ultra-small nanorod-constructed platinum nanocubes directly grown on the ITO substrate and their heterogeneous catalysis application,” RSC Advances, vol. 3, pp. 19789–19792, 2013.

[5] M. I. Stockman, “Nanoplasmonic sensing and detection,” Science, vol. 348, no 6232, pp. 287-288, 2015.

[6] M. Morsin, M. M. Salleh, A. A. Umar, and M. Z. Sahdan, “Gold nanoplates for a localized surface plasmon resonance-based boric acid sensor,” Sensors, vol. 17, pp. 947-955, 2017.

[7] O. V. Shapoval, K. Kobayashi, and A.I. Nosich, “Electromagnetic engineering of a single-mode nanolaser on a metal plasmonic strip placed into a circular quantum wire,” IEEE J. Sel. Top. Quant. Electron., vol. 23, no 6, 2017. DOI: 10.1109/JSTQE.2017.2718658

[8] I. S. Maksymov, “Magneto-plasmonic nanoantennas: basics and applications,” Rev. Phys., vol. 1, pp. 36-51, 2016.

[9] S. J. Lee, A. R. Morrill, and M. Moskovits, “Hot spots in silver nanowire bundles for surface-enhanced Raman spectroscopy,” J. Am. Chem. Soc., vol. 128, no 7, pp. 2200–2201, 2006.

[10] A. Kozorezov, C. Lambert, F. Marsili, and M. J. Stevens, “Quasiparticle recombination in hotspots in superconducting current-carrying nanowires,” Phys. Rev. B, vol. 06, pp. 123-126, 2015.

[11] Y. Tang, L. Sun, and A.E. Cohen, “Chiroptical hot spots in twisted nanowire plasmonic oscillators,” Appl. Phys. Lett., 102, 043103, 2013.

[12] T. Itoh, Y. S. Yamamoto, Y. Kitahama, and J. Balachandran, “One-dimensional plasmonic hotspots located between silver nanowire dimers evaluated by surface-enhanced resonance Raman scattering,” Phys. Rev. B, vol. 95, pp. 115441, 2017.

[13] N. P. Stognii and N. K. Sakhnenko, “Sensitivity of hybrid plasmons in nanowire based triangular/square clusters to surrounding dielectric environment,” Proc. URSI General Assembly and Scientific Symp. (URSI-GASS-2014), art. no 2065, Beijing, 2014.

[14] N. P. Stognii and N. K. Sakhnenko, “Theoretical study of plasmon excitation of a Drude metal nanowire coupled with optically dynamic shell,” Proc. In. Conf. Electron. Nanotechnol. (ELNANO-2017), pp. 205-208, Kiev, Ukraine, 18-20 April, 2017.

[15] J. S. Sekhon, H. K. Malik, and S. S. Verma, “Tailoring surface plasmon resonance wavelengths and sensoric potential of core–shell metal nanoparticles,” Sens. Lett., vol. 11, pp. 512–518, 2013.

[16] L. Mahmudin, E. Suharyadi, A. B. S. Utomo, and K. Abraha, “Optical properties of silver nanoparticles for surface plasmon resonance based biosensor applications,” J. Mod. Phys., vol. 6, pp. 1071-1076, 2015.

[17] K. Li, M. I. Stockman, and D. J. Bergman, “Self-similar chain of metal nanospheres as an efficient nanolens,” Phys. Rev. Lett., vol. 91, no 22, pp. 227402-4, 2003.

[18] C. Hoppener, Z. J. Lapin, P. Bharadwaj, and L. Novotny, “Self-similar gold-nanoparticle antennas for a cascaded enhancement of the optical field,” Phys. Rev. Lett., vol. 109, pp. 017402-4, 2012.

[19] G. Pellegrini, M. Celebrano, M. Finazzi, and P. Biagioni, “Local field enhancement: comparing self-similar and dimer nanoantennas,” J. Phys. Chem. C, vol. 120, no 45, pp. 26021–26024, 2016.

[20] N. P. Stognii and N. K. Sakhnenko, “Excitation of plasmon resonances on nanowire and nanoshell by complex source point,” Proc. Int. Conf. Adv. Optoelectron. Lasers (CAOL-2016), pp. 129-131, Odessa, 2016.

[21] P. Jonson and R. Christy, “Optical constants of the noble metals,” Phys. Rev. B, vol. 6, pp. 4370-4379, 1972.

[22] D. M. Natarov, V. O. Byelobrov, R. Sauleau, T. M. Benson, and A. I. Nosich, “Periodicity-induced effects in the scattering and absorption of light by infinite and finite gratings of circular silver nanowires,” Opt. Expr., vol. 19, no 22, pp. 22176–22190, 2011.

[23] V. O. Byelobrov, T. M. Benson, and A. I. Nosich, “Binary grating of sub-wavelength silver and quantum wires as a photonic-plasmonic lasing platform with nanoscale elements,” IEEE J. Sel. Top. Quant. Electron., vol. 18, no 6, pp. 1839-1846, 2012.

[24] N. Stognii and N. Sakhnenko, “Plasmon resonances and their quality factors in a finite linear chain of coupled metal wires,” IEEE J. Sel. Top. Quant. Electron., vol. 19, No. 3, 4602207, 2013.

[25] D. M. Natarov, R. Sauleau, M. Marciniak, et al., “Effect of periodicity in the resonant scattering of light by finite sparse configurations of many silver nanowires,” Plasmonics, vol. 9, no 2, pp. 389-407, 2014.

[26] D. M. Natarov, M. Marciniak, R. Sauleau, and A. I. Nosich, “Seeing the order in a mess: optical signature of periodicity in a cloud of plasmonic nanowires,” Opt. Expr., vol. 22, no 23, pp. 28190–28198, 2014.