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ON OPTIMUM OF EM ENERGY TRANSPORT ALONG 1D NANOSCALE SIMPLE METAL WAVEGUIDES WITH └- AND ┴-JUNCTIONS

Within the framework of the RPA method it was modelled the passage of an electromagnetic signal along a one-dimensional nanoscale structure immersed in a dielectric medium – a linear array of silver nanoparticles of spherical shape. The mentioned nanoscale 1D-array was considered as a waveguide. The signal that travels along the nanosized chain was considered as the plasmonic wave and it was described with allowance for the Lorentz friction. The remarkable feature of this study was the fact that one needed to calculate the efficiency of signal propagation along a linear array of nanospheres of radius a_0, which is the key parameter for nanospheres with the minimum attenuation of dipole oscillations when they occur. For silver nanospheres the value of the "special" radius a_0 is about 9 nm. The center-to-center distance d between the particles was accepted as $d=3a_0$. The author considered a "long" nanochain: it supposed that its length is more than 500 nm. Due to considering metal nanospheres with special radius of a_0 such arrays can demonstrate minimum damping when plasmonic waves travel along the structures: through not only straight structures as well as bent ones (with ∟-corners) and branched ones (with ⊥-junctions). In this work it was calculated two characteristics of signal transmission through bent and/or branched nanoscale waveguides – the Power Transmission Coefficients ($PTC_{L,T}$) and the Linear Attenuation Rates ($LAR_{L,T}$) per 500 nm of waveguide length. The calculated value of the averaged LAR was about 1 dB per 500 nm for vacuum medium and about 0.6 dB per 500 nm for Silica glass medium. Calculations based on the proposed model are in good agreement with independent experimental data and obtained results are very close to the calculated data obtained by other researchers who used the TDLDA method. This speaks certainly in favor of a more accurate method of random phase approximation.

***Keywords**: surface plasma oscillations; plasmonics; metallic nano-chain; nanoscale waveguides; energy transport.*

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ОПТИМАЛЬНОЕ ПРОХОЖДЕНИИ ЭМ СИГНАЛА ВДОЛЬ ОДНОМЕРНОГО ВОЛНОВОДА ИЗ НАНОЧАСТИЦ ПРОСТЫХ МЕТАЛЛОВ, ВЫПОЛНЕННОГО С ИЗГИБАМИ И РАЗВЕТВЛЕНИЯМИ

В рамках RPA-модели исследовано прохождение ЭМ сигнала вдоль одномерной наномасштабной структуры (длинная цепочка из наносфер серебра), помещенной в диэлектрик. Указанная структура рассматривалась как волновод для незатухающих плазмонных волн. В модели учитывалось трение Лоренца. Особенностью данного моделирования были расчеты для наносфер радиуса a_0, который соответствует минимальному затуханию возникающих в наночастицах дипольных колебаний. Для серебряных наносфер это около 9 нм. Вторым важным параметром цепочки было межцентровое расстояние. Расчеты, проведенные на основе предложенной модели, хорошо согласуются с независимыми экспериментальными данными.

***Ключевые слова**: поверхностные плазменные колебания, наномасштабные волноводы, передача ЭМ энергии.*

Introduction

Experimental and theoretical studies of plasma oscillations in metallic nanoparticles, in addition to purely scientific interest, are also of great practical importance [1–11]. In this case, as it shown by experiments [8, 12–20], the frequency both of the plasma and the light waves may coincide, but the length of the plasma wave will be significantly less than the length of the light wave [3, 14–21]. This fact allows to avoid the diffraction limits for light circuits when one transforms the light signal into the plasmon-polariton wave [4, 8, 9, 13, 15–18, 21]. It is found that one-dimensional periodic structures of metallic nanoparticles can serve as plasmon waveguides with low damping [4, 5, 14, 15, 20–23]. This is treated as prospective for the forthcoming construction of plasmon optoelectronic nano-devices that are not available in ordinary lightwave-guides, because of diffraction constraints. Therefore considered chains of nanoparticles can be successfully used in modern optoelectronic devices [2, 5, 6, 8, 15, 18, 21]. When studying plasma oscillations in nanoparticles as small as 5 nm or less, the method of quantum-mechanical density functional theory or the "local-density approximation" method (LDA) as well the "time-dependent LDA" method (TDLDA) are generally used [3–6, 8, 11].

The random phase approximation (or RPA-method) was developed as semi-classical scheme to describe volume plasmons in bulk metals (for simple metals) and it can be successfully applied when studying plasma oscillations as well in calculations concerning plasmon excitations in large metallic nanoparticles (metal spheres with radius about 10–100 nm) [9, 10, 19–24].

The volume plasma oscillations within metallic nanoparticles can give rise to forced oscillations on the surface of nanoparticles [9, 10]. As it already shown [10, 19–21], after arisen in *individual particles* plasma oscillations can attenuate due to the processes of electron scattering and radiation losses, through the Lorentz friction force in particular. Of course, the study of the properties of *ensembles of nanoparticles*, for example linear structures, is of the great practical interest: such structures can work as effective 1D-waveguides [1, 2, 4, 5, 8, 14, 15, 17, 20–23]. Researchers and technologists call such linear arrays of metal nanoparticles by nanoscale chains: these chains can be composed of nanoparticles of different shapes – rods, ellipses, spheres [4, 12, 15, 18, 20, 21].

As one can see from their geometric characteristics, similar linear arrays composed of metallic nanospheres of radius a have two parameters – the nanosphere diameter $2a$ and the distance d between the particles (most often it is the center-to-center distance). If we consider such a nanochain as a 1D periodic structure, then the nanoparticles are arranged equidistantly in it, i.e. $d = const$, and the value of d one can call as the period of a given linear structure.

The next question is the ratio of the distance d to the nanosphere radius a: it is most often one considered the ratio of $d/a = 3$ to be closer to optimal [4, 5, 10, 13, 14, 19–23]. So, in this paper one considers exactly the same ratio.

Now about the total length L of such a linear array, or about the length L of a metal nanochain. Let it be that $L = N \cdot d$, where N is the number of such periods of the given structure. In order to be more formal, we can call the given array as "a long chain" if N >>1. But more often one considers that "the long nanochain" is an array that is longer than 500 nm.

This work is aimed to calculate within the framework of RPA method some characteristics of linear $\llcorner$- and $\perp$-shaped structures composed of silver nanospheres as EM waveguides placed into different dielectric medium and then analyze obtained results. Unlike other models and approaches to the similar problems of plasmon wave passage along 1D-arrays, this problem was solved accurately using RPA.

Let us consider a metallic nanoparticle of a spherical shape of radius a, which is placed in a dielectric medium ($\varepsilon \geq 1$, $\mu = 1$) and located in an external alternating electric field. Suppose that the external magnetic field is zero. Let the material for a given nanosphere be a simple metal. Since we are only interested in the behaviour of conduction electrons of the metal nanosphere, we use the well known "*jellium model*" [24–26], which allows us to replace the positive charge of lattice ions by a uniformly distributed charge over the entire volume of a nanoparticle whose density is equal to $n_e(r) = n_e\Theta(a - r)$, where $n_e = N_e/V$, $n_e|e|$ – the average positive charge density, N_e – the number of conduction electrons in this nanosphere, $V = 4\pi a^3/3$ is it's volume, Θ stands for the Heaviside step function.

Suppose that up to certain event (i.e., t=0) the electron gas of the metallic nanoparticle was in a state of equilibrium. Let it be at the time of t=0 a homogeneous electric field appeared and immediately disappeared near this particle. As a result of this perturbation, surface dipole plasma oscillations arise in the metallic nanosphere. The dipole moment of the particle corresponding to these oscillations depends on time and emits electromagnetic waves, and the radiation of the electromagnetic wave, in turn, is accompanied by the force action $\vec{f}_L$ of the emitted field on the electrons of the nanoparticle. This effect is called "*radiation retardation*" or Lorentz friction force [10, 19, 21]. The presence of this force is equivalent to the presence of an external effective electric field $\vec{E}_L = \vec{f}_L(t)/eN_e$, whose source is in the center of the metallic nanosphere. Thus, in this case, at t>0, the time dependence of the dipole moment of a nanoparticle is given by the following equation (*see* [21, 23]):

$$\frac{\partial^2}{\partial t^2}\vec{D}(t) + \frac{2}{\tau}\frac{\partial}{\partial t}\vec{D}(t) + \omega_{p,h}^2\vec{D}(t) = \varepsilon_h\omega_{p,h}^2 a^3\vec{E}_L(t), \tag{1}$$

where $\omega_{p,h} = \omega_p/\sqrt{3\varepsilon_h}$ – the intrinsic frequency of the dipole type surface plasmon; ω_p – the plasma frequency of electron gas. The value $1/\tau$ which enters into (1) (*see* [10, 19, 21]):

$$\frac{1}{\tau} = \frac{v_F}{2}\left(\frac{1}{\lambda_B} + \frac{1}{a}\right) + \frac{\omega_{p,h}}{3}\left(\frac{a\cdot\omega_p}{c\sqrt{3}}\right)^3 = \frac{1}{\tau_0} + \frac{\omega_{p,h}}{3}\left(\frac{a\cdot\omega_p}{c\sqrt{3}}\right)^3 \tag{2}$$

is the damping of plasma oscillations, which arises as a result of the interaction of conduction electrons with each other, as well as with the vibrations of the crystal lattice (the 1st term in (2)), and as a result of the interaction of the conduction electrons with the surface of the metallic nanoparticle (the 2nd term in (2)). The values v_F and λ_B represent the Fermi velocity and the mean free path of the electron in bulk metal, respectively. The 3rd term in (2) expresses taking into account the Lorentz friction in our considering.

Actually, here the first term of the sum of (2) (i.e. $v_F/2\lambda_B$) describes the interaction of plasma oscillations with metal phonons and therefore grows with increasing temperature, but does not depend on the dimensions of the nanoparticle. The second term (i.e. $v_F/2a$) describes the interaction of plasma oscillations with the surface of the nanoparticle, so it depends not on the temperature but on the radius of the nanoparticle.

It can be seen from relation (2) that the value of $1/\tau$ grows at $a \to 0$ and for $a \to \infty$, and the attenuation of dipole oscillations has its *minimum* value at the radii of metallic nanospheres equal to

$$a_0 = \frac{\sqrt{3}}{\omega_p}\sqrt[4]{\frac{c^3 v_F\sqrt{3}}{2}}\ . \tag{3}$$

The minimum attenuation at $a = a_0$ means that at $a > a_0$ the plasma oscillations damping increases with increasing radius of the nanosphere, and the eigen-frequency $\omega^*_{p,h} = \omega_{p,h} \Big/ \sqrt{1 - 1/(\omega_{p,h} \cdot \tau)^2}$ of the dipole moment oscillations of a metallic nanoparticle decreases (to be more clear: it is for *individual* nanoparticle in a dielectric medium). When $a < a_0$ the damping $1/\tau$ value also increases: it means the eigen-frequency $\omega^*_{p,h}$ decreases, but this time with a decrease of the radius a of the nanosphere [19–21]. This fact is confirmed experimentally [19, 20]. As for the corresponding calculations for silver nanoparticles, immersed into vacuum and Silica glass (SiO_2, ε_h =3.8 [27]) they show, that the radius a_0 of minimal damping of plasmon oscillations for the metal is about 10 nm (see Table 1).

So, below one will consider some properties and characteristics of silver nanospheres of radius a0 (see Table 1), and then consider the waveguide efficiency of linear structures composed of nanoparticles of this size.

Propagation of surface plasma oscillations along a linear chain composed of metal nanoparticles

Consider a "long chain" composed of metallic nanoparticles of spherical shape of radius a_0 and placed in a dielectric host medium with dielectric constant of ε_h. Suppose that these nanospheres are located along the $\boldsymbol{Z}$ axis in such a way that their centers are at an equal distance d from each other: here is $d = 3a_0$ (see Fig. 1). Since a nanochain more than 500 nm in length is usually considered to be "long", for the current case the author considers linear arrays with $N \geq 20$.

Table 1

The values of the Silver nanospheres radii, which correspond to the minimum attenuation coefficients (at 300 K)

The host medium	The nanosphere radius a_0, nm
vacuum (ε_h =1)	8.35

Let the origin of coordinates be in the center of one of the nanospheres (for example, for l=0). Suppose that at time t=0 there are plasma surface dipole oscillations arise under the influence of an external δ-shaped electric field in metallic nanoparticles of the chain. These dipole oscillations induce a time-dependent electric dipole moment $\vec{D}$. Therefore, nanoparticles begin to emit electromagnetic waves, which, in turn, are absorbed by neighbouring particles. And this process – the radiation and absorption of electromagnetic waves by the nearest particles – is repeated many times in the described linear nanoscale array. Thus, collective excitations can propagate along the chain, i.e. dipole waves travel from one nanosphere to another.

Let the distance d between metallic nanoparticles be much smaller than the length of the electromagnetic wave λ emitted by any particle of the chain (i.e. d/λ <<1). This is equivalent to the fact that the nanospheres which are adjacent to the selected particle will be in the dipole zone of the emitted electromagnetic wave. Here is the equation that describes such waves [21]:

$$\left(\frac{\partial^2}{\partial t^2} + \frac{2}{\tau_0} \frac{\partial}{\partial t} + \omega^2_{p,h} \right) \vec{D}(t) = \omega^2_{p,h} \varepsilon_h a^3 \vec{E}(t) . \quad (4)$$

The radiative losses of oscillating charges (that is plasmon dipole variations in time) can be displayed by the Lorentz friction [21, 28, 29]: $\vec{E}_L = \dfrac{2}{3c^3} \dfrac{\partial^3}{\partial t^3} \vec{D}(t)$. So, one can rewrite (4) including the Lorentz friction term:

$$\left(\frac{\partial^2}{\partial t^2} + \frac{2}{\tau_0} \frac{\partial}{\partial t} + \omega^2_{p,h} \right) \vec{D}(t) = \omega^2_{p,h} \varepsilon_h a^3 \left(\vec{E}(t) + \vec{E}_L \right). \quad (5)$$

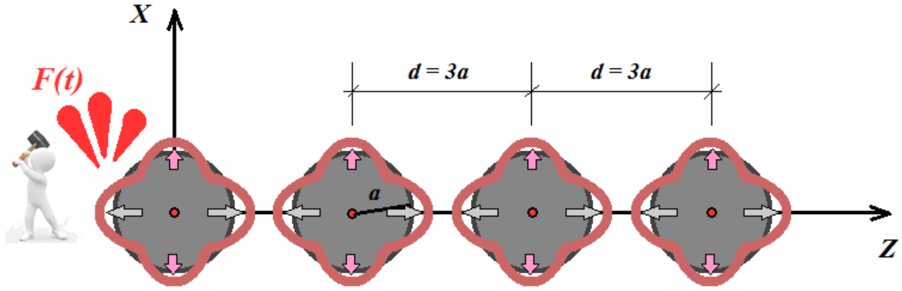


Fig. 1. A schematic representation of the linear array of metallic nanospheres of radius a, which are immersed into dielectric and spaced by a distance of d (here $d = 3a_0$)

Substituting $z = l \cdot d$ one can determine the dipole moment of the particle located at the l -th node of the considered infinite chain [21, 23]:

$$\left(\frac{\partial^2}{\partial t^2} + \frac{2}{\tau_0}\frac{\partial}{\partial t} + \omega_{p,h}^2\right) D_z(ld,t) = \omega_{p,h}^2 \varepsilon_h a^3 \left(\sum_{\substack{m=-\infty \\ (m \neq l)}}^{+\infty} E_z(R_m, R_{ml}, t) + E_{Lz}(ld,0,t) + E_{0z}(ld,0,t) \right) \quad (6a)$$

$$\left(\frac{\partial^2}{\partial t^2} + \frac{2}{\tau_0}\frac{\partial}{\partial t} + \omega_{p,h}^2\right) D_x(ld,t) = \omega_{p,h}^2 \varepsilon_h a^3 \left(\sum_{\substack{m=-\infty \\ (m \neq l)}}^{+\infty} E_x(R_m, R_{ml}, t) + E_{Lx}(ld,0,t) + E_{0x}(ld,0,t) \right) \quad (6b)$$

The Equations (6a) and (6b) describe the dipole-type coupling between the arranged nanospheres (Fig. 2). As one can see, all the terms in (6a) and (6b) are “dimension-sensitive” values, i.e. they rigidly depend on the geometric parameters of such waveguides.

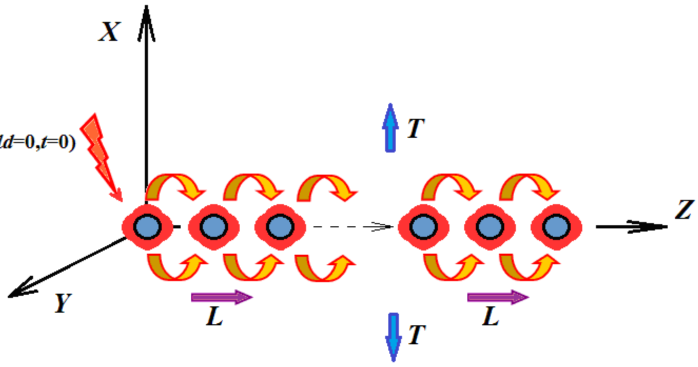


Fig. 2. The illustration of surface plasma oscillations propagation along a linear array made up of spherical metallic nanoparticles: the process is based on the dipole-type coupling between the arranged nanospheres

Let us analyze the electric field “behavior” of propagating plasma oscillations caused by an external source of the field at the frequency range near the resonance of a given system of nanoparticles. When solving these Equations (6a) and (6b) using the Fourier transformation with the corresponding boundary conditions and nearby the resonance frequencies, one can obtain the following equations concerning the electric field strength $E_{z,x}(ld,a,t)$ of the travelling plasmon wave:

$$E_z(ld,a,t) = \frac{2}{3}\omega_{p,h}^2 b_{0z}(\phi) E_{0z}(0,0) \cdot \left(\frac{1}{\varepsilon_h} - \frac{2aF_z}{c\sqrt{\varepsilon_h}} \cos(u_{0z} l) \cdot \sin\left(F_z t + \delta_{0z}(F_z)\right) \right); \quad (7a)$$

$$E_x(ld,a,t) = -\omega_{p,h}^2 b_{0x}(\phi) E_{0x}(0,0) \times$$
$$\times \left[1 - \frac{R_\omega F_x}{\omega_{p,h}} \cos(u_{0x} l) \cdot \left(\sin\left(F_x t + \delta_{0x}(F_x)\right) + \frac{R_\omega F_x}{\omega_{p,h}} \cos\left(F_x t + \delta_{0x}(F_x)\right) \right) \right] \quad (7b)$$

Here (for both polarizations – z and x, i.e. the longitudinal and transverse ones) one has:

- $E_{0z,x}(0,0)$ – the amplitudes of the electric field strength oscillations at “starting” node, i.e. that node of the nanoscale metallic chain where the external source of the field is located;
- $u_{0z,x} \in [0;2\pi]$;
- $b_{0z,x}(\phi) = 1 \Big/ \sqrt{(\omega_{0z,x}^2 - F_{z,x}^2)^2 + 4F_{z,x}^2 / \tau_0^2}$;
- $\delta_{0z,x}(F_{z,x}) = arctg\left(\dfrac{2F_{z,x}}{\tau_0(\omega_{0z,x}^2 - F_{z,x}^2)} \right)$.

Then let it be: $F_{z,x} = P_{z,x}\left(1 + \phi / P_{z,x}\right)$, where the following is true:

$P_z = \omega_{p,h} \cdot \sqrt{1 - 4(a/d)^3 \cos(\pi Q_z/2)}$	$P_x = \omega_{p,h} \cdot \sqrt{1 + 2(a/d)^3 \cos(\pi Q_x/2)}$
$Q_z = 1 - \sqrt{\frac{1}{3} - \frac{9}{\pi^2}\left[R^2 + \frac{v_F}{R}\left(\frac{\sqrt{3\varepsilon_h}}{\lambda_B \omega_p} + \frac{1}{cR}\right)\right]}$	$Q_x = 1 - \sqrt{\frac{1}{3} + \frac{9}{\pi^2}\left[R^2 + \frac{2v_F}{R}\left(\frac{\sqrt{3\varepsilon_h}}{\lambda_B \omega_p} + \frac{1}{cR}\right)\right]}$

$$R = \omega_p a / c\sqrt{3};$$

- $\phi = \left|\omega_{z,x(1D)} - \omega_{0z,x}\right|$, where $\omega_{z,x(1D)} = 1 / \sqrt{\omega_{0z,x}^2 - 1/\tau_0^2}$ is the frequency of the eigenwaves in a 1D-array composed of the same particles. And ϕ is such value that is true: $\phi / P_{z,x} << 1$ and $F_{z,x}^2 - P_{z,x}^2 \approx 2\phi \cdot P_{z,x}$.

And Her Majesty Practice asks its own questions, for example: what will the attenuation of the signal be in case of passing of it through such branch structures as ∟-corners and/or ⊥-junctions?

Of course, when solving this problem, it is necessary to take into account such basic principles of Nature as continuity of EM waves and the conservation laws.

In this (the current) case, these will be two *rules*: the continuity of plasmonic waves and the law of conservation of the EM-energy flux [26, 30]. And it is well known fact that the efficiency of the EM-signal travelling depends on the geometry of the certain structure, the signal frequency, and polarization directions of the plasmonic waves that enter and exit the structure [4]. In this paper basic (and the simplest!) junctions are considered: ∟-junctions (i.e. 90°-corners) and ⊥-junctions.

A signal travels along the chain, and after reaching the particle that can be called a *splitting node* the signal splits and can change its own polarization. In the figures (*see insets in* Table 3) this particle is marked with a circle. If a signal $E_{input} = E(ld = 0; a = a_0; t = 0)$ appears at the input of the structure, then its output intensity E_{output} can be calculated. Results of signal attenuation calculating are shown below. Note that the length of each bend ("shoulders") in these junctions is 500 nm.

Calculations of the signal damping were made for nanoscale one-dimensional waveguides: the author considered chains of silver spherical nanoparticles as such waveguides placed into different dielectric media, for example, in vacuum (ε_h=1) and Silica glass (SiO_2, ε_h=3.8 [27]). All the parameters of signal damping are calculated for the ambient temperature of 300 K. In the table below one can see the results of calculations of the signal damping when it runs along linear nanosized waveguides composed of silver spherical nanoparticles of radius $a = a_0$ (*see* Table 1 *above*) and spaced by distance of $d = 3a_0$. Since it was considered nanoscale metallic chains composed of nanospheres of certain size of a_0, then we can expect maximum efficiency of signal travelling via the waveguide. In his calculations the author assumed that the total length of the metallic nanochain exceeded 500 nm.

The presented data below show some characteristics concerning to the signal attenuation when it (the signal) travels along a straight metallic nanochain (*see* Table 2), and the signal runs along 1D bent and branched waveguides (*see* Table 3). In both cases the waveguides were placed in dielectrics.

The Table 2 shows the obtained data on attenuation of the signal intensity when it runs along the mentioned nanosized silver waveguides for different dielectric medium. One considers two characteristics of signal transmission for both polarization modes – the Power Transmission Coefficients ($PTC_{L,T}$) and the Linear Attenuation Rates ($LAR_{L,T}$) per 500 nm of waveguide length. It is obviously that the signal transfers with high efficiency along the mentioned waveguides under the given conditions.

Table 2

Attenuation of the Signal Intensity when it travels along the mentioned nanosized waveguides for different dielectric medium: the Power Transmission Coefficient ($PTC_{L,T}$) and the Linear Attenuation Rate ($LAR_{L,T}$)

(silver nanospheres, radius $a = a_0$, center-to-center distance $d = 3a_0$, T°=300 K)

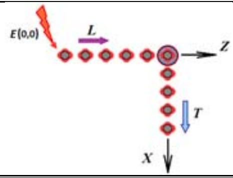
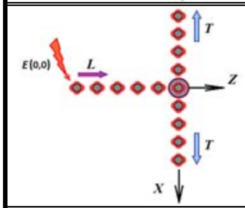
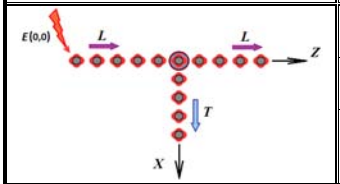
The Host Medium	Longitudinal Propagation		Transversal Propagation	
	radius = a*$_0$ *(see Table 1)		***radius = a*$_0$ *(see Table 1)***	
	PTC_L, *a.u.*	**LAP_L, dB/500nm**	**PTC_T, *a.u.***	**LAP_T, dB/500nm**
vacuum (ε_h=1)	0.894	0.97	0.934	0.60
SiO_2 (ε_h=3.8)	0.882	1.09	0.930	0.63

As for the next question – on signal travelling through curves and branches: the author had chosen three structures and calculated the corresponding parameters – the power transmission coefficients (*see* Table 3).

Table 3

The Signal Intensity when it travels along Silver nanosized waveguides through ∟-corners and ⊥-junctions for different dielectric medium: the Power Transmission Coefficient ($PTC_{L,T}$)

(Ag-nanospheres, radius= a_0 , center-to-center distance $d = 3a_0$, T°=300 K)

The Type of Junction	Vacuum (ε_h =1)		SiO_2 (ε_h =3.8)		by M. Brongersma ***et al.*** [4]
	E_{z_input} =	0.882	E_{z_input} =	0.894	---
	$E_{z\to x\_output}$ =	0.820	$E_{z\to x\_output}$ =	0.835	*0.889*
	E_{z_input} =	0.882	E_{z_input} =	0.894	---
	$E_{z\to x\_output}$ =	0.410	$E_{z\to x\_output}$ =	0.417	*0.500*
	E_{z_input} =	0.882	E_{z_input} =	0.894	---
	$E_{z\to z\_output}$ =	0.453	$E_{z\to z\_output}$ =	0.472	*0.640*
	$E_{z\to x\_output}$ =	0.429	$E_{z\to x\_output}$ =	0.422	*0.320*

The Table 3 presents the calculated data concerning to the intensity of the signal that passes along the Ag-nanochain and reaches its certain point – the special node of the waveguide which causes a reversal of the signal polarization (in the picture the point is marked with a circle). It is assumed that up to this point and from this point the travelling signal will pass through equal "shoulders" (pathways) which are 500 nm of length. So, "input" and "output" represent input and output values of the signal intensity correspondingly. For comparison, one can see the values of the calculated intensities taken from the study of M.L. Brongersma *et al*. [4].

Summary

In this paper it is reported on calculating of two characteristics of signal transmission through bent and/or branched nanoscale waveguides – the Power Transmission Coefficients ($PTC_{L,T}$) and the Linear Attenuation Rates ($LAR_{L,T}$) per 500 nm of waveguide length.

An important feature of this study was consideration of the plasmonic waves' passage through a 1D-array of Ag-nanospheres of the special size – of the radius a_0 which provides minimum signal damping.

These two characteristics of signal transmission were found for both polarization modes – for the Longitudinal and the Transverse ones. The computed values were obtained within RPA and they are exact solutions of the problem. The obtained results are in good agreement with similar results of other researchers.

These calculated values of the attenuation rate of plasmon waves (*see* Table 2) can indicate a high efficiency of this described above method of transmitting EM-energy along such waveguides. The author believes that such nanoscale waveguides can be successfully used for subwavelength transmission lines within integrated optics circuits.

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