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LIGHT PROPAGATION CHARACTERISTICS OF OPTICAL METAL DIELECTRIC COAXIAL NANO-WAVEGUIDES WITH COMPLEX SHAPES

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Исследована волноводная структура нано-размерного поперечного сечения, изготовленная из благородных металлов и диэлектрика. Рассмотренный тип волновода позволяет передавать оптическое изображение с суб-волновым разрешением на расстояния, значительно превышающие его поперечное сечение при малых потерях. На основе метода конечных элементов проведена оценка затухания и длины распространения излучения в волноводе, установлена возможность сильной локализации поля в центральной диэлектрической части структуры. Рассмотрены волноводы с циркулярной и эллиптической формами поперечного сечения.
КЛЮЧЕВЫЕ СЛОВА: плазмонные волноводы, коаксиальные волноводы, благородные металлы, численное моделирование, нано-размерное сечение.

Досліджено хвилевідну структуру нано-розмірного поперечного перетину, яка виготовлена з благородних металів і діелектрика. Розглянутий тип хвилеводу дозволяє передавати оптичне зображення з суб-хвильовою роздільною здатністю на відстані, що значно перевищують його поперечний перетин при малих втратах. На основі методу кінцевих елементів проведено оцінку загасання і довжини розповсюдження випромінювання в хвилеводі, встановлено можливість сильної локалізації поля в центральній частині діелектричної структури. Розглянуто хвилеводи з циркулярною і еліптичною формами поперечного перетину.
КЛЮЧОВІ СЛОВА: плазмонні хвилеводи, коаксіальні хвилеводи, благородні метали, числове моделювання, нано-розмірний перетин.

The properties of new optical waveguides with nanosize cross-section made of noble metals and glasses are described. This waveguide supports propagation of modes with unusual propagation properties. For estimation of the field localization, losses, propagation length, velocity and others characteristics the numerical simulations by FEM method has been used. Coaxial waveguide with the annular and the elliptic central rods are considered. The comparatively low value of losses has explained.
KEYWORDS: plasmonic waveguides, coaxial, noble metals, numerical simulations, nano-size.

INTRODUCTION

Artificial optical systems consist of subwavelength elements (waveguides, resonators, etc.) have recently been proposed, studied, and engineered. The subwavelength sizes refer here only to waveguide cross-sections which should be much smaller than half-wavelength, $\lambda/2$. The creation of the optical nano-size waveguides to support the propagation of light to a needed distance with small losses is very important for many applications. As known, there are various kinds of photonic crystal fibers including fibers with subwavelength channels for transmission of radiation in optical range. However, electromagnetic fields localization is limited by few microns in these fibers. One of the promising ways to miniaturize optical waveguides is to use surface plasmon-polaritons propagating in noble metals. However, light propagation length is very short in plasmonic waveguides as compared with optical fibers. Thus, a very important task is to reduce absorption losses in waveguides keeping their nanoscale sizes. Different types of plasmonic waveguides have been studied: metal films of different width [1], hollow metal waveguides [2], metal cylinders with and without dielectric core [3], coaxial waveguides [4]. For some applications closed waveguides are preferable since they provide confinement of light inside the waveguide cross section. At the same time, reduction of the cross section causes usually the increase of attenuation. It was found in [4] that some modes in metal coaxial waveguides exhibit considerably lower losses compared with hollow plasmon waveguides at optical frequencies. Fields of these modes are the result of interaction of plasmons and electromagnetic waves in the air region. It is an attractive idea to use coaxial cables similar to applied at radio frequencies. In such waveguides, made of perfect electric conductor (PEC) metals in radio and microwave technique, the TEM mode can propagate without cutoff.

In this paper we investigate coaxial waveguides in which the bulk inner metal rod is replaced by one or several thin metal annuluses. The phase velocity of the dipole-like mode in this waveguide is close to the speed of light. We compare optical properties of such a waveguide with a conventional coaxial.

THEORY AND RESULTS

In the optical range the electromagnetic properties of metals are described by a complex dielectric constant. The real part is negative and the imaginary part takes into account losses. It is important to notice, that for noble metals (silver, gold), the losses remain small and the imaginary part of the dielectric constant can be much smaller than its real part. The propagation constant is directly related to the effective refractive index of the mode $\beta = n_{eff}\omega/c$, where c is speed of light. In general, n_{eff} is a function of the frequency ω and it depends upon the geometry and on the type of mode. In the lossless case for propagating modes β is real and it is purely imaginary for evanescent modes.

We present the results of the numerical simulations by FEM method which used is a direct numerical solution of Maxwell equations with proper boundary conditions. The equation in this case as follow,

$$\nabla((\varepsilon - \frac{j\sigma}{\omega\varepsilon_0})^{-1}\nabla \times \vec{H}) - \mu K^2 \vec{H} = 0 \quad (1)$$

The solution of this equation is

$$\vec{H} = \vec{H}(x, y)\exp(i\beta z) \quad (2)$$

where ε – is the permittivity, ε_0 – is the vacuum permittivity, σ – is the electric conductivity, μ – is the relative permeability, β - is the propagating constant, $K=\omega/c$, $n_{eff}=\beta/K$.

Silver is used as the metal and the glass with the refractive index n_g = 1.5 is used as the dielectric. Complex refractive index of silver n_s for that wavelength was taken from [6]: n_s = 0.05 + i3.13, and the corresponding permittivity is: $\varepsilon_s = n_{2s}$ = -9.794+ i0.313. The distance of light propagation along the waveguide is determined by $n_{eff}{}''=Im(n_{eff})$ and the estimated propagation length can be calculated as $L = \lambda/(4\pi n_{eff}{}'')$. We focus our attention on dipole-like modes as easily excited by dipoles. As known, these modes play main role in extraordinary transmission through two-dimensional sub-wavelength arrays of coaxial holes [5].

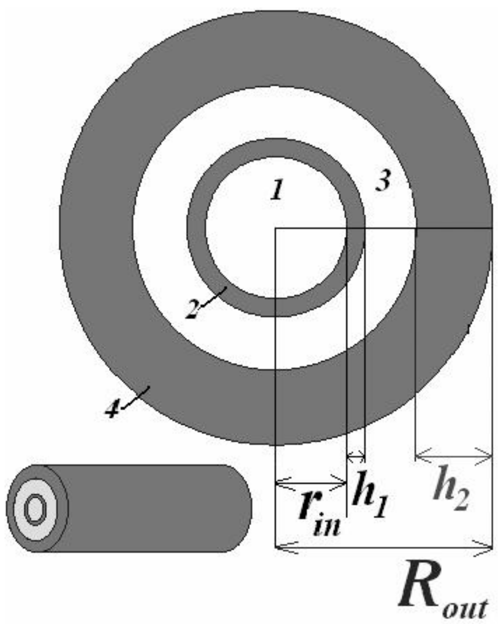

Fig 1. The schematic view of the coaxial waveguide with circular shape. The coaxial waveguide consisting of two nano-sized metal tubes (annuli in cross sections; grey areas 2 and 4) with a dielectric material between them (white area 3) and an inner road filled with the same dielectric (white area 1).

We consider a coaxial waveguide consisting of two nano-sized metal tubes (which look as annuli in cross sections) with a dielectric material between them and an inner road filled with the same dielectric, see Fig. 1. Parameters of this structure are the following: r_{in}=45nm, h_1=5nm, h_2=70nm, R_{out}=150nm. The radius R_{out} is chosen by such a way that the metallic outer boundary does not affect the propagation characteristics. We present results of the simulations for the wavelength λ=500 nm.

In Fig. 2 power flow distribution for the dipole-like mode is shown using artificial colors for intensity coding. blak color corresponds to the highest intensity. The effective refractive index of this mode is n_{eff} = 0.742 + i0.026, so its real part is considerably lower than the refractive index of glass. Arrows show the electric vector field. The electric field vector distribution corresponds to the dipole-like character of this mode. Such waveguides support propagation of the different type of modes. The mode present on the Fig. 2 has a smallest losses and longest propagation length. This structure supports propagation of different types of modes. We observed all of them and conclude that they have higher attenuation. Those modes don't present here due to restrict length of this paper.

We compare optical properties of such a waveguide with the conventional coaxial waveguide. All existed modes have considerably higher losses than the dipole-like mode in the coaxial with the annular cross-section, presented of Figure 2.

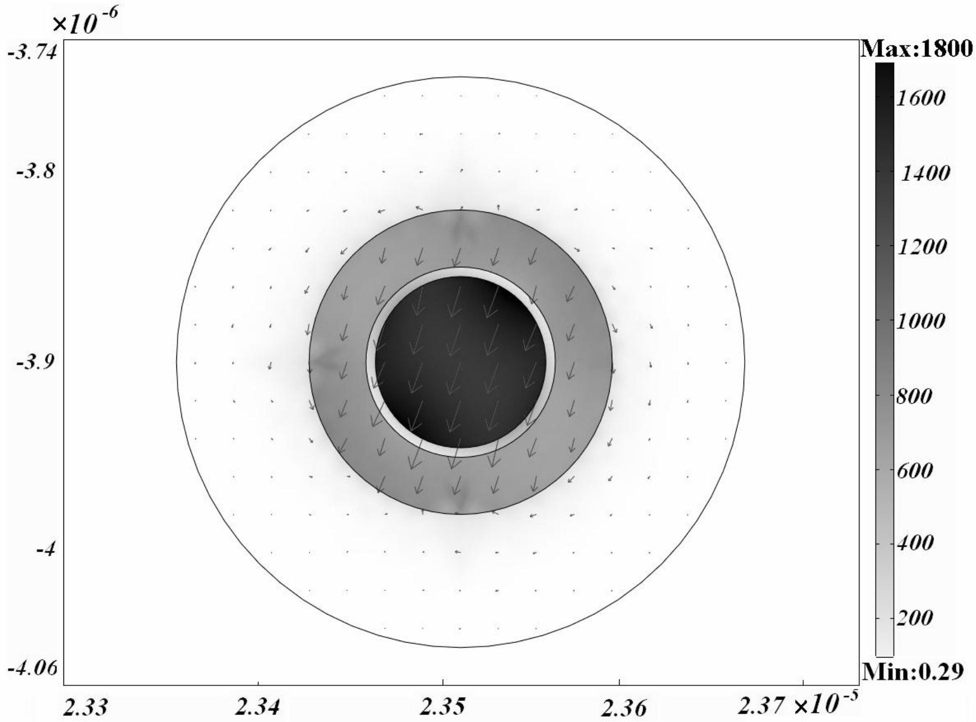

Fig. 2. Power flow distribution for the various modes in the case r_{in}= 45nm, h_1=5nm, h_2=70nm, R_{out}=150nm. (a) The dipole-like mode, n_{eff} = 0.742+i0.026, L = 1500 nm.

Then we consider another type of the coaxial nanosize waveguide. We propose to surround the central part with periodically arranged align tubes. The model of the coaxial waveguide, consisting of many nano-size metal tubes, is shown in Fig. 3.

In this case, if to cut periodically annuluses in the metal outer shell, we reduce the metal part in the structure. This allows of stronger field localization in the inner dielectric part and small attenuation for fast modes (propagating with the phase velocity exceeding speed of light in the glass). Appropriate choice of cuts makes possible to improve confinement of the field in the central area, see Fig. 3.

In this work we investigated the effect of the wavelength deviation from fixed value. All previous results have been performed for λ=500nm. As easy to see from the table 1, the results are approximately similar for wavelength region from 490nm to 520nm. The strong field localization and intensity are similar too. We don't give the appropriate figures due to limited length of the paper.

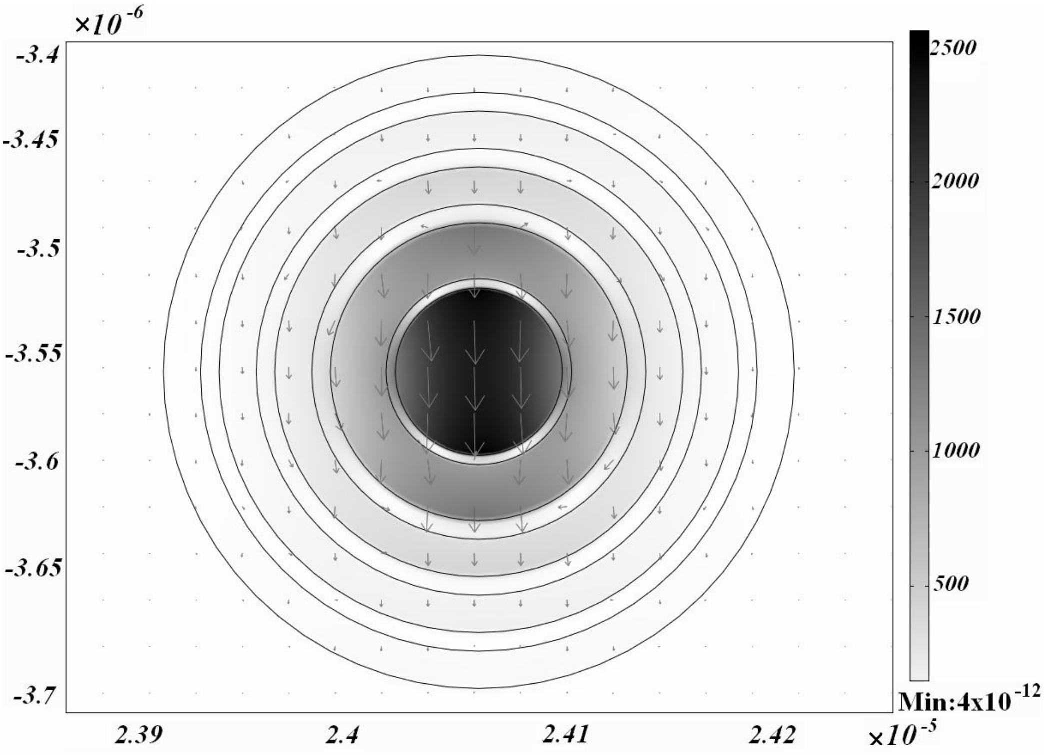

Fig. 3. Power flow distribution for the dipole-like mode in case r_{in}=45 nm; $h_{silver1}$=5 nm; $h_{glassr1}$=30nm; $h_{silver2,3,4}$=10 nm; h_{glass}2,3,4 =20 nm; $R_{out} \to \infty$; n_{eff} = 1.010+ i0.0245, L = 1670 nm.

Table 1. The parameters of the low-losses mode for structure with two nano-sized metal tubes (as on Fig.1(a)) for different values of the wavelength. The parameters of the structure as before (see Fig.2 (a)).

λ **(nm)**	***Re(n)***	***Im(n)***	***L* (nm)**
490	0.801	0.025	1.592
500	0.742	0.026	1.530
510	0.636	0.031	1.283
520	0.620	0.032	1.243

Let us consider eigenmodes propagating in nano-cables with elliptic-type rods and rods with a shape of crossed ellipses. Figure 4 illustrate the electric field distribution of the dipole-like mode in the coaxial with the elliptic central rod. The filling medium is glass. The external radius of structure is R_{out} = 150 nm and h_2 = 70 nm, as before. The large ellipse semi-axis is 45 nm, the small ellipse semi-axis is 25 nm. Effective refractive index is n_{eff} = 1.67 + i0.018 for the dipole-like mode. The dipole-like mode is faster and it possesses lower attenuation. The dipole-like mode, propagating in the coaxial with the circular central rod, having radius 45 nm, is characterized by the effective refractive index n_{eff} =2.61+i0.36. Thus, a modification of the central rod shape significantly changes both real and imaginary parts of the effective refractive index for the dipole-like mode.

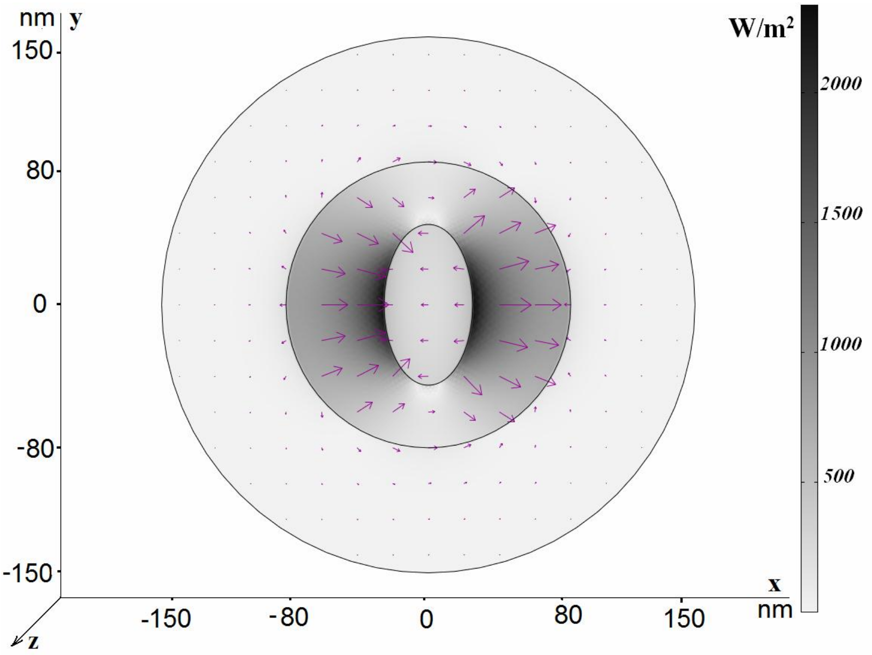

Fig. 4. Power flow distribution for the dipole-like mode in the case R_{out} = 150 nm, h_2 = 70 nm; the large ellipse semi-axis is 45 nm, the small ellipse semi-axis is 25 nm. The electric field vector is shown by arrows. The dipole-like mode n_{eff} = 1.67 + *i*0.018.

Earlier we proposed a coaxial with the central rode with the shape of two crossed ellipses [7]. Typical electric field distribution in such a coaxial is shown in Figure 5. The use of two crossed ellipses allows one to transmit independently two orthogonal polarizations with equal values of the effective refractive index. Each of these modes can be excited by an electric dipole (of the orthogonal polarization) and such waveguides can be used for transfer a dual-polarized field distribution, creating a dual-polarized image with a sub-wavelength resolution at a distance from the source. This structure also supports propagation of the TEM-like mode with the refractive index n_{eff} = 3.022 + *i*0.042, see fig.5. We pay a special attention to the dipole-like modes because they can be easer excited by electric dipoles.

Electric field distribution for the dipole-like mode is shown in Figure 5. The imaginary part of the effective refractive index is larger than for similar mode in the coaxial with the elliptic central rod but is practically the same as for the TEM-like mode both in the coaxials with one ellipse and crossed ellipses.

CONCLUSION

In conclusion, we have demonstrated that the strong subwavelength field localization can be achieved for the dipole-like mode in coaxial waveguide having glass filled annulus as the central rods. Other plasmonic-like modes have considerably high attenuation factor. We have studied the coaxial waveguide with periodically cut annuli and have found that appropriate choice of parameters allows phase velocity to be close to the speed of light in free space that can make easier excitation of the coaxial by an external dipole. Considered waveguide structures can be fabricated using the state-of-the-art techniques for producing photonic crystal glass. Complicated micro- and nanostructures manufacturing is possible via multiple redrawing and sintering of glass stacks [8]. Such nano-sized waveguides can be used, for example, as optical near-field probes and for transfer of images with subwavelength resolution.

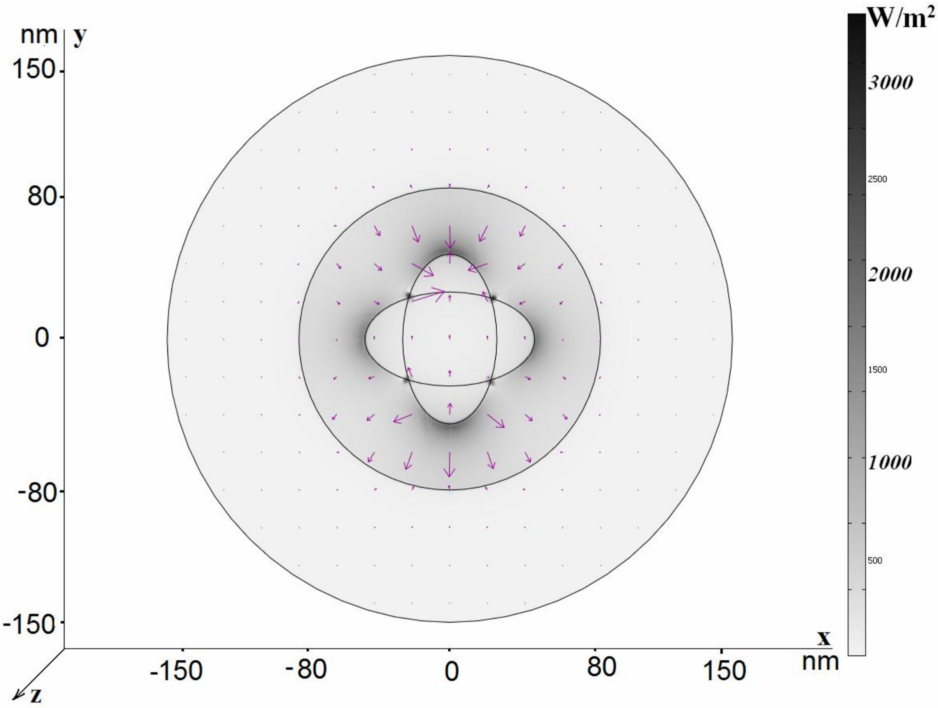

Fig. 5. Power flow distribution for the dipole-like mode in the case R_{out} = 150 nm, h_2 = 80 nm; the large ellipse semi-axis is 45 nm, the small ellipse semi-axis is 25 nm. n_{eff} = 2.396 + i0.045.

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