Simulation of plasmons on a metal nano-ring

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Abstract. Using the finite difference time domain method, it is shown that a laser beam with a wavelength of 633 nm and circular polarization forms on the silver nano-ring with a width of 260 nm a surface plasmon polariton with a full width at half maximum of 0.25\(\lambda\), and the maximum intensity of 1.873 a. u.

1. Introduction
Today, much attention is paid to the plasmon polaritons which propagate along the metal-insulator interface and arise in connection with the collective oscillation of free electrons\[1\textsuperscript{-}2\]. Plasmons, due to their special properties, have a large scope in various fields of science: physics, chemistry, biology, materials science, etc.\[3\textsuperscript{-}5\].

It was shown in\[6\], that high intensities of plasmonic fields during catalysis are a powerful tool for achieving higher reaction rates and/or better selectivity. The phenomenon of surface plasmon polariton allows increasing the sensitivity of chemical and biological sensors\[7\]. Optical components based on plasmon effects are considered as an ideal choice for the fabrication of nano-integrated optical circuits\[8\]. The use of surface plasmon polaritons allows for the use of subwavelength optics in microscopy and lithography beyond the diffraction limit\[9,10\].

As can be seen from the above review, surface plasmon polaritons have a large number of different applications. One of them could be optical capture and manipulation of microparticles\[11\textsuperscript{-}13\]. In our previous papers, we investigated the formation of a surface plasmon on a silver nano-strip and a nano-ring while illuminating by laser light of a wavelength equal to 532 nm\[14\]. In this study, we make similar research for the incoming radiation with a wavelength of 450 nm and 633 nm.

2. Formation of the surface plasmon polariton on a nano-strip
In\[14\] it was shown, that a resonant surface plasmon polariton could be formed on the surface of a nano-strip or nano-ring. The appropriate strip width should be selected for it. However, its disadvantage is that the maximum intensity is formed at the edges, and the peaks are very close to each other. Using such a field to capture and manipulate particles is problematic. At the same time, it is possible to form a central plasmon-polariton, the peak of which is located in the central part. Although the intensity of the central plasmon is much lower than the intensity of the resonant plasmon, the use of a single plasmon seems to be more convenient.

To determine the appropriate width of the nano-ring, the effect of the formation of central and resonant plasmons on a thin (20 nm thick) silver strip placed in the air was investigated. While the simulation the width of the strip was changed with a step of 10 nm to obtain the dependence of the intensity of the formed plasmons on the width of the nano-strip.
The simulation was conducted by using frequency depended finite difference time domain method ((FD)^2TD-method), implemented in FullWAVE package. The next parameters were used: spatial grid size is 2 nm, pseudo time step (τ = ct, c is the speed of light, t is time) is 1 nm. Materials permittivities were described by the Sellmeyer model [15] and the Drude-Lorentz model [16] and presented in Figure 1.

Figure 1. The dependence of permittivity of silica glass [15] and silver [16] on the wavelength of the incident light.

The main condition for the excitation of surface plasmon polaritons is the difference in signs of the real parts of the permittivities of the media on which interface the plasmonic wave propagates. The greater the difference between them, the stronger the plasmonic effects. Therefore, it can be concluded from Figure 1 that plasmons should be stronger for higher wavelengths. To check the theory we considered the TM-polarized beams with a wavelength of 633 nm and 450 nm as the incident light.

Figure 2 shows that it is difficult to obtain central plasmon on the nano-ring surface while illuminating it by a beam with a wavelength of 450 nm. The intensity of resonant plasmon is higher than the intensity of the central plasmon for the most values of the ring width. Only at a small gap, two lines are quite close so we selected the following values of the nano-ring width for further research: 120 nm and 140 nm.

Figure 3 shows that the well-formed central plasmon-polariton with minimal side lobes should be expected at the width of the nano-ring from this gap. At other points, the boundary plasmons have
more high intensity and reach a maximum at the resonance width of the nano-strip. Based on the obtained data we selected the following values of the nano-ring width for further research: 220 nm and 260 nm.

**Figure 3.** The dependence of the maximum intensity of the boundary (continuous line) and central (dashed line) surface plasmon polariton on the width of the nano-strip for TM-polarized beam with a wavelength of 633 nm.

It can be seen from Figure 3 that at some points two graphs of the intensities coincide. A well-
It should be noticed, that the gap for the wavelength of 633 nm is wider than for the wavelength of 450 nm. It means that fabrication errors will have a smaller influence on the formation of the central plasmon in if the wavelength is bigger.

3. **Formation of the surface plasmon polariton on a nano-ring**

In the previous section, we defined the intervals for the nano-rings width at which a well-formed central plasmon is expected. It is also shown in [14] that the difference in the refractive index of the medium and the substrate, on which a nano-ring in a thin silver film is fabricated, produces fluctuations during the formation of the central plasmon. In this regard, similarly to previous studies, it is proposed to consider water with a refractive index $n_{H2O} = 1.38$ as a medium in this paper.

We consider the propagation of laser light with a wavelength of 450 nm and 633 nm, normally incident on a silver nano-ring on a quartz substrate located in water. To satisfy the conditions of the plasmon excitation we choose radial polarization. The scheme of the numerical experiment is shown in Figure 2 where his a height, or is the width and Din is the inner diameter of the nano-ring. Light is shown by red arrows and propagates along the Z-axis. The simulation was conducted by using FullWAVE package implemented (FD)2TD-method. Hereinafter, the following simulation parameters were used: steps in space were 8 nm, steps in pseudo time was 2 nm.

**Figure 4.** Simulation scheme.
To set the radial polarization, the input field was calculated in the MATLAB package and set in FullWAVE from the file. The following formula was used for the calculation:

\[
\begin{align*}
E_x &= \frac{2\sqrt{2} \cdot x}{\delta} e^{\frac{x^2+y^2}{\delta^2}}; \\
E_y &= \frac{2\sqrt{2} \cdot y}{\delta} e^{\frac{x^2+y^2}{\delta^2}},
\end{align*}
\]

(1)

where \( E_x \) and \( E_y \) are the electric field components and \( \delta \) is the Gaussian beam width.

The radius of the Gaussian beam for both components \( E_x \) and \( E_y \) was chosen equal to 0.5 μm, and the maximum intensity was normalized. The inner diameter of the nano-ring \( D_{in} \) was also chosen to provide falling of the maximum intensity of incident light on the center of the nano-ring. Figure 5-8 shows the simulation results.

![Figure 5](image)

**Figure 5.** The intensity distribution on the surface of a nano-rings with a thickness of 120 nm (a) and 140 nm (b).

Figure 5 shows that formed surface plasmon-polariton is quite weak. The maximum intensity of the formed on the surface of the nano-ring plasmonic field is 1.216 a.u.

![Figure 6](image)

**Figure 6.** 2D intensity distribution on the surface of a nano-ring with a thickness of 120 nm (blue line) and 140 nm (red line).

It can be seen from Figure 6 that there are no central plasmon on both nano-rings and the maximum intensity is formed on the edges of the nano-ring.

Figure 7 shows that a central plasmon polariton is formed on the ring surface. The maximum intensity of the plasmonic field on the surface of a 260 nm wide ring is 1.873 a.u. and at the same
time, it is higher than the maximum intensity of plasmon on the surface of a narrower ring, which is 1.364 a.u.

**Figure 7.** Intensity distribution on the surface of a nano-rings with a thickness of 220 nm (a) and 260 nm (b).

**Figure 8.** 2D intensity distribution on the surface of a nano-ring with a thickness of 220 nm (red line) and 260 nm (blue line).

Figure 8 shows that the full width at half-maximum of plasmons intensity is FWHM = 158.4 nm for a wide ring and FWHM = 186.8 nm for a narrow. The simulation results show that the nano-ring allows the formation of a narrow plasmon-polariton on its surface, the thickness of which coincides with the thickness of a similar plasmon formed by radiation with a length of 532 nm [14].

4. **Conclusion**

In this work, using the FDTD method, we studied the formation of surface plasmon polaritons on the nano-stripes and nano-rings. It is shown that a nano-ring with a width of 260 nm illuminated by a light beam with a wavelength of $\lambda = 633$ nm and circular polarization, forms a surface plasmon-polariton with a full width at half maximum of $0.25\lambda$, which is equal to the width of a similar plasmon formed by a beam with a wavelength of 532 nm (FWHM = 0.29$\lambda$) [14].

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