Bulletin of Pure and Applied Sciences.
Vol.39 D (Physics), No.1,
January-June 2020 P.45-48
Original Research Article

Print version ISSN 0970 6569
Online version ISSN 2320 3218
DOI: 10.5958/2320-3218.2020.00007.X
Available online at www.bpasjournals.com

Resonant Properties of Circular Optical Nanoantennas of Homogeneous Disks

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Received on 31.01.2020
Accepted on 23.04.2020

ABSTRACT We have studied the resonant properties of circular optical nanoantennas as well as other shapes of optical antennas without requiring any fitting parameters. This allows for a deeper insight into scaling behavior and do faster further research since a desired simple tool is now available to design such nanoantennas. The theory has been applied to design antennas supporting various resonances at predefined frequencies to respond to the desire to have multi resonant antennas for applications. Raman sensors are extremely broad band resonators. Such circular patch nanoantennas consist in tailoring the dispersion relation and the complex reflection coefficient at will by carefully selecting a particular stack of layers. We have made to characterize the resonance behavior of the potentially simplest optical nanoantennas which is also called nanowire antennas. The nanowire as a plasmonic cavity, a resonance occurs when the phase accumulated on a single round trip amounts to multiple of 2π . This phase is determined by the propagation constant of the plasmonic mode supported by the nanowire and an additional phase on reflection at the wire termination. By fitting many resonance positions with different nanowire lengths, the phase change on reflection is determined. Such results are obtained only for a few simplified geometries. Nanoantennas are made from an arbitrary stack of homogeneous disks. Increasing the radius of a single disk toward infinitely and increasing its thickness yielded the reflection coefficient of surface Plasmon polariton propagating along a single metallic interface at a planar termination. The obtained results were in good agreement with previous results.

KEYWORDS Resonant, nanoantenna, sensor, resonator, patch, tailoring, dispersion, reflection coefficient, stack, optical, plasmonic cavity.

INTRODUCTION

The metallic antennas at radio frequencies, where the metal is considered as perfect conductor be conveniently treated analytically using Babinet's principle causes to hold in the visible range[1-3]. The dielectric functions of metals have to be accounted for may be described by the free electron model. The arising plasma oscillations couple to the electromagnetic radiation at a metallic interface to form new confined quasi particles[4-5]. These quasiparticles are termed as surface Plasmon polaritons and govern the resonant behavior of optical nanoantennas[6]. Such optical nanoantennas have enabled ubiquitous applications[7-9] and can be used for many applications. Eigen modes of various nanoantennas have been measured by different means[10-12]. Problematic in further advancing the field is the lack of analytical insight into the scaling behavior of optical nanoantennas to carefully design them for a desired applications[13-15]. Spectral domain has been reached due to advances in nanofabrication and characterization techniques[16]. Despite of this progress the theoretical understanding of optical nanoantennas is lagging behind the available technology. Efforts in this direction have been made to characterize the resonance behavior of the potentially simplest optical nanoantennas. Resonance can be explained by Fabrot-Perot model. Tedious procedures were necessary since the analytical calculation of the complex reflection coefficient turned out to be fairly involved. Such results are available for a few simplified geometries[17-19]. Predicting the complex reflection coefficient of surface plasmons at abrupt interfaces is one of the key issues to be solved for a future advances in nanophotonics. We made study for the complex reflection coefficient of Hankel surface Plasmon polaritons at the circumference of the circular patch nanoantennas was analytically calculated. Our work is analytical tool for deeper insight into the scaling behavior of complex nanoantennas and defined a path how to treat such nanooptical system analytically where only these approaches have been used.

METHOD

For calculation of complex reflection coefficient we have used Hankel surface Plasmon polaritons model. To describe the actual field we have used a plasmonic mode that takes finite values at the origin. These modes are Bessel-type surface Plasmon polaritons and it is written as

$$E_z^{m,-}(\rho,z)=J_m(k_{SPP}\rho)\,a(z) \qquad \text{….. (1)}$$

Where SPP is surface plasmonic polariton which is used in localized condition. The phase change on reflection of one dimensional nanoantennas causes a deviation of the resonance condition. The apparent length change is explained by the reflection phase and the same approach has been used. The reflection without phase accumulation the resonant radii $R_{n,m}$ of order n is given by the roots of $E_z^{m,-}$ leading to the roots of Bessel functions as for circular microstrip patch antennas. For introducing a non zero phase on reflection we have conjectured the real valued resonance condition which is written as

$$2k_{SPP}^{'}R_{n,m}+\phi_m^r=2x_n(J_m) \qquad \text{….. (2)}$$

where x_n presents the nth root of $J_m, k_{SPP}=k_{SPP}^{'}+ik_{SPP}^{''}$. This is extension of the Fabry-perot resonance condition for one dimensional nanowire antennas. Resonances are obtained by solving $2k_{SPP}^{'}L_n+2\phi^r=2\pi n$.

Different numerical methods have been used to achieve this. The finite difference time domain simulations have been taken for the purpose. The assumed Bessel form and scaling of E_z was studied. Metallic disks of different thickness were used as circular nanoantennas at a fixed frequency. A resonator model was used to calculate the resonance frequencies of a circular nanoantenna with fixed geometrical parameters. The obtained results were compared with previously obtained results.

RESULTS AND DISCUSSION

Figure 1 shows the phases ϕ_1^r of calculated values. Phases corresponding to different thickness differ significantly. The obtained results show a monotonic behavior between thickness d and phase on reflection ϕ_1^r. We have found that for the thicker disk the larger reflection phase occur

$\phi_1^r(d_1) < \phi_1^r(d_2) < \ldots$ for $d_i < d_{i+1}$. All ϕ_1^r turn out to be negative; the only exception arises in two thickest disks for small radii. The relative change of ϕ_1^r from the first to the fifth resonance radius amounts approximately 10% to 30%. It increases with thickness. The resonant radii $R_n \equiv R_{n.1}$ were determined by identifying maxima of the electric field strengths below and above the structure while changing the radius of disks at a constant thickness. The fields as predicted by equation (1) were compared with full wave simulations and an excellent agreement was observed. The fields at nanoantenna resonances follow exactly such as Bessel type surface Plasmon polaritons. The resonance radii are linearly related to the roots of J_1 as assumed in equation (2). Resonant radii R_n have been explained by an analytically calculated phase of the reflection coefficient for the excited even modes by using equation (2). The comparison of numerically and analytically calculated resonant radii has been plotted in graph (2). The predictions for even modes coincide with numerical simulations for thickness upto 80nm. We found that for a given thickness the theory predicts a series of resonance radii that are in full agreement with numerical results. We found that for increasing the thickness the resonance radii are independent of the thickness. Theory was also tested for isolated metallic disk and was found that this is also applicable for stacked nanoantennas. Stacks introduced a much larger degree of freedom for tailoring the properties of Bessel type surface Plasmon polaritons for propagation constant and reflection coefficient at the disk termination.

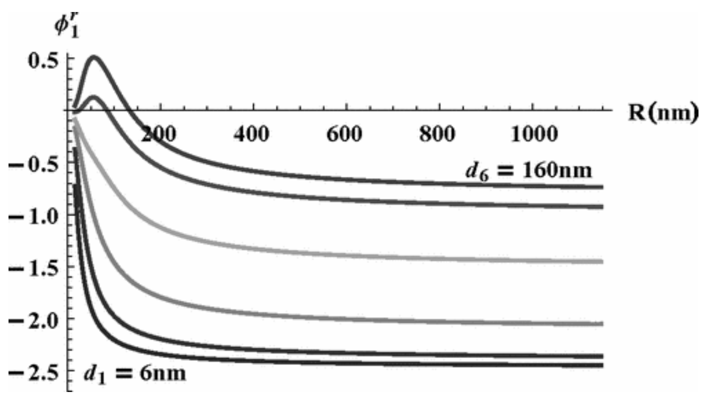

Figure 1: Phases on reflection vs. the disk radius calculated from the theoretical model for metallic disks.

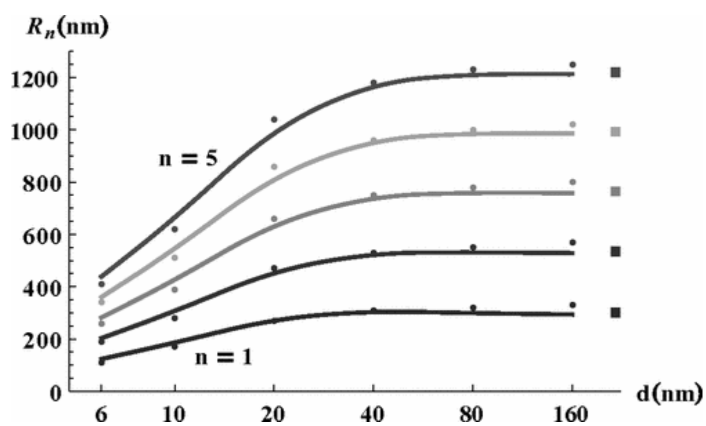

Figure 2: Analytically calculated phases of the reflection coefficient for disks of different thicknesses *d*. The five lowest-order resonances are shown. Results from rigorous simulations are shown by dots. Large squares correspond to R_n resulting from calculations assuming a semi-infinite disk; hence, the thickness *d* is infinite.

CONCLUSION

We have studied the characteristics of resonant behavior of the potentially simplest optical nanoantennas. The resonance was explained by Fabry-Perot model. Resonances occurred when the phase accumulated on a single round trip amounted to multiple of 2π . The phase was determined by the propagation constant of the plasmonic mode supported by the nanowire and additional phase reflection at the wire termination. By fitting many resonance positions with different lengths and incidence angles the change on reflection was determined. The resonance properties of optical circular nanoantennas were studied for stack of homogeneous disks. We have calculated the phase accumulation of surface Plasmon polaritons across the resonator and additional contribution from the complex reflection coefficient at the antenna termination by using analytical model circular optical nanoantennas are tuned by varying the stack. The complex reflection coefficients of Hankel surface Plasmon polaritons at the circumference of the circular patch nanoantennas were analytically calculated. Increasing the radius of a single disk towards infinity and increasing thickness yielded the reflection coefficient of on surface Plasmon polariton propagating along a single metallic interface at a planar termination. The obtained results were compared with previously obtained results of theoretical and experimental works and were found in good agreement.

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