Modelling 1-D Copper Grating for Extraordinary Optical Transmission

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Research Article

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Abstract

The excitation of surface plasmon polaritons (SPPs) and its association with extraordinary optical transmission (EOT) has been presented in this report.. The 1-dimensional periodic grating structure of copper (Cu) has been designed over the glass substrate in rf-module of COMSOL Multiphysics 5.3a. The geometry was illuminated from glass side with visible-near infrared (400-900nm) electromagnetic spectrum. The 0th order transmission spectra have been investigated to study the maximum value of EOT at different slit widths by taking the period (700nm) and thickness of Cu grating (50nm) constant. Moreover, the near field analysis has been used to investigate the field behavior at desired interface and to verify the results of transmission spectra. It is worth mentioning that the highest value of EOT corresponds to the slit width of 250nm which is affiliated with the strongest plasmonic mode i.e., fundamental plasmonic mode. Such devices are increasingly applicable in sensing, chemical and solar cell industries.

Introduction

Optical transmission through the sub wavelength has become the area of great interest due to its remarkable applications in the real-life sensible devices since 1998 [1]. It was first described by Bethe which predicated that the transmission of light through sub wavelength varies by the $(\lambda /r)^2$. Here, λ is used for wavelength while r for the radius of the slit/aperture [2]. When the light falls on periodically-arranged grating structure, it produces two modes: one diffracted mode produced far away from interface of light with the metal and another evanescent mode produced at the interface. The evanescent mode generates the oscillation of electric or magnetic fields on surface of metal which increases the wave vector of the incident light. Due to increment in wave vector of incident light, its momenta, coupled with the momenta of collective oscillation of free electrons at the surface of metal, produces the surface plasmon polaritons (SPPs) [3–10].The phenomenon of coupling momenta of oscillation of electrons and incident light is known as surface plasmons resonance (SPR). The scattering of light after passing through the subwavelength slit causes the enhanced transmission of light and referred as enhanced optical transmission [11–13]. Enhanced optical transmission depends upon incident light, geometry and relative permittivity of metal. Such device structures have many applications in biosensing ultrafast detectors and photolithography. In order to clear concept that how the light interact with with small structure many efforts have been reported i.e. computation approach of cylindercal particle coated at silver surface, transfer matrix technique and numerical calculation for many 1D periodically nanostructure [14, 15]. F. J. García-Vida *et al*. [16] have studied three methods of enhanced optical transmission by using slit wavelength mode, groove cavity mode and in phase groove transmission. This type of phenomena that occurred due to nanohole array has been presented by Zhiquan Chen [17]. A group of researchers [18] calculated maximum EOT varies from 46% for nanosphere and 56% for nanocylinder. Evan S. H. Kang *et al*. studied EOT and concluded that it increases with an increase in the thickness of metal [19].

In this work, the enhanced optical transmission through 1D grating of nanostructured Cu has been presented. The COMSOL Multiphysics 5.3a was utilized for the simulation of the grating with a period of 700nm and thickness 50nm over the glass substrate. The maximum value of EOT has been obtained by varying slit width of the grating from 50-450nm. Taking into account the high cost of other metals, the Cu metal has been used here compromising the other factors. It is very interesting to report the 1D metallic grating structure which is unique and easy to fabricate.

Theory And Numerical Modeling

Electromagnetic (EM) wave, when strikes with the unit cell of any substance, becomes polarized and its subdomain gives information about the physical properties like electric conductivity (σ), relative permittivity and relative permeability of the substance. Basically these properties tells about the charges and currents which were on the substance by using the Maxwell equation.

When an incident wave falls on slit 'a' of grating after interaction with slit, it excites the metal and gets scattered at the interface of Cu/air caused by SPPs excitation. The path of light, interacting the grating with the several diffraction modes, has been presented in figure 1.

The light is incident on the grating structure, as a result the coupling of light occurs and the SPPs are formed at the Cu/air interface. 1. The reason behind this can be described by equation 1. **See equation 1 in the supplementary files section.**

The RF-module in COMSOL Multiphysics has been utilized for the modeling of desired geometry. The modeled geometry with all the domains and boundary conditions has been shown in figure 2 and material is assigned to all sub domains from the reference [20].

The model has been designed with periodicity of 700nm in order to make it compatible with the real life device. The thickness of Cu-grating has been taken as 50nm which is in accordance with the optical depth. For saving the computational cost, the unit cell is loaded with the specially designed periodic boundary conditions. For the collection of light, the ex-port has been bounded with scattering boundary conditions. For the fine and accurate execution of models, the meshing with elemental size of 20nm has been applied with triangular shape. The in-port has been incident with TM light at normal incidence for the efficient coupling with the surface plasmons at Cu/air interface.

Results And Discussions

This excitation technique provides efficient coupling of SPP to the incident light at Cu/air interface. After illuminating the model from substrate side, the transmission spectrum has been extracted from the model after interaction of light with grating as shown in figure 3. It is well known that only p-polarized light can cause the excitation of SPPs hence s-polarized light is of no use.[21, 22] The constructive and destructive interference of electromagnetic radiations with metallic electrons is the reason behind the maxima R_2 and minima R_1 respectively. As the peak R_2 is responsible for the EOT [23] hence it is focused on the further calculations.

Moving towards the calculation of EOT, the models with different slit width have been illustrated with transverse electric (TE) and transverse magnetic (TM) light. The interaction of TE light with the surface plasmons causes the excitation of SPPs at Cu/air interface which was confirmed by dip R_1 in figure 3. The ratio of transmission for TE to the TM corresponds to the EOT which is plotted in figure 4 against range of slit width 50-450nm. It is worthy to mention that the maximum value of EOT occurs at slit width between one half to two third of periodicity which corresponds to the fundamental plasmonic mode well known in literature [24, 25]. The reason behind maximum EOT in this specific region of slit width, for the 1D metallic grating structure the smaller slit width causes lesser scattering of light [26] as compared to the wider slit width which causes lesser scattering and so its efficiency value is low for coupling of incident light and SPP, at the start the transmission of light is higher just because of direct scattering [26]. Mostly in 1D grating devices, the smaller value of slit width corresponds to the highest plasmonic modes which exists at the cu/air interface because of higher Fourier components which later resulted in overwhelming efficiency of 0^{th} order fundamental plasmonic , instead of this when slit width increased the higher plasmonic disappeared in the grating devices [27-30].

In order to visualize the enhancement of field, the plot parameters package of COMSOL has been used. The -field and -field at the Cu/air interface has been significantly enhanced as clearly seen in figure 5. The models are clearly evident of the coupling of surface plasmons with electromagnetic radiations hence causing excitation of SPPs and field enhancement at the desired interface which is in accordance with equation 1.

The transmission spectra in figure-4 have been obtained by performing the Far-field analysis and to support the results obtained from Far-field analysis the near-field analysis has been performed. The field at Cu/air interface has been checked by drawing a line and studying cross-sectional plots in the software. The excitation of SPPs corresponds to the enhancement of the fields at the interface of grating and dielectric hence such results are of special concern in order to verify the results of transmission.

The values of E-field and B-field against slit width have been presented in figure 6 which evidently indicates that the field is maximum at slit width 250nm. This confirms the optimum value of slit width which is also in line with previous literature because such value corresponds to the fundamental mode of plasmonics.

Conclusion

In present work, excitation of SPP along Cu/Air interface has been reported by using 1D grating devices designed in COMSOL module at the optimum thickness of Cu film of 50nm on a higher refractive index (RI) of Glass substrate. A modest way has been used to estimate the EOT by recording the transmission spectra which is obtained by using 0th order transmission spectra for the plasmonic grating structure of varying slit width and fixed periodicity of 700 nm. Optimum Value of EOT obtained at one third to one half of periodicity. The maximum field confirms the maximum EOT at slit width half to the two-thirds (250nm) of periodicity which corresponds to fundamental plasmonic mode. The study is in line with the results published previously [31]. The marvel of EOT produced by light through metallic nano-hole arrangements has concerned noteworthy consideration owing to its potential applications for ultrasensitive label-free biosensing and massive color filters.

Declarations

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Figures

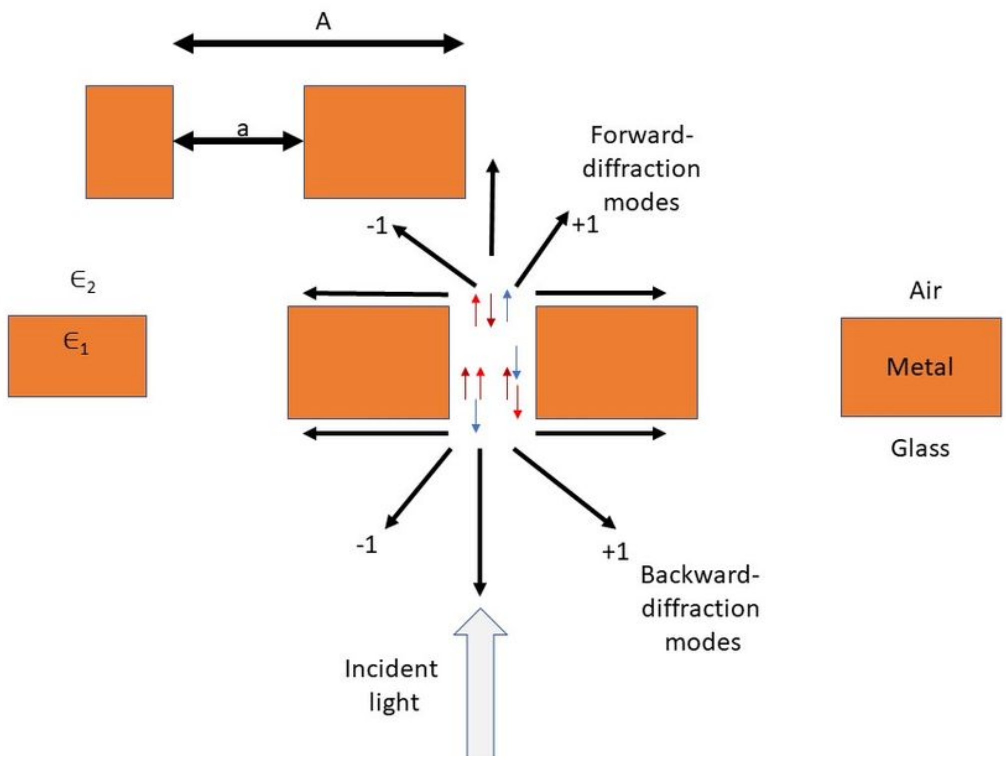

Figure 1

Illustration of modes of diffraction for illumination under p and s polarization.

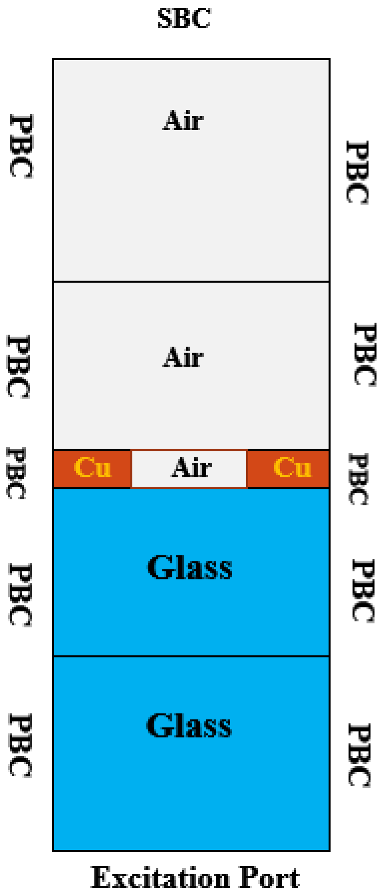

Figure 2

The modeled unit cell with all the subdomains and boundary conditions.

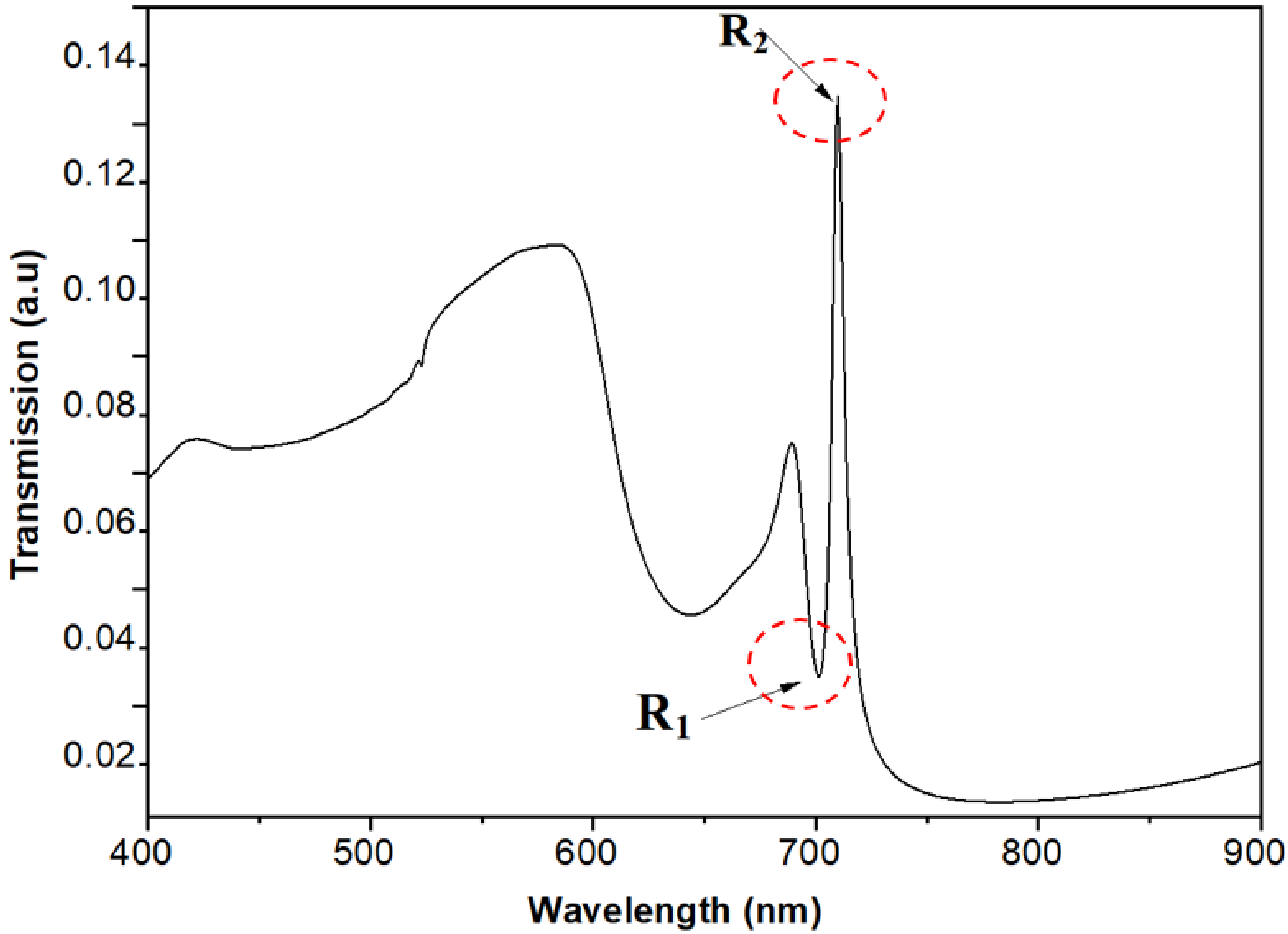

Figure 3

Transmission spectrum from 1D grating device with thickness 50nm and periodicity 700 nm under p-polarized excitation. The dip R1 and peak R2 are the characteristic features associated for the calculation of EOT.

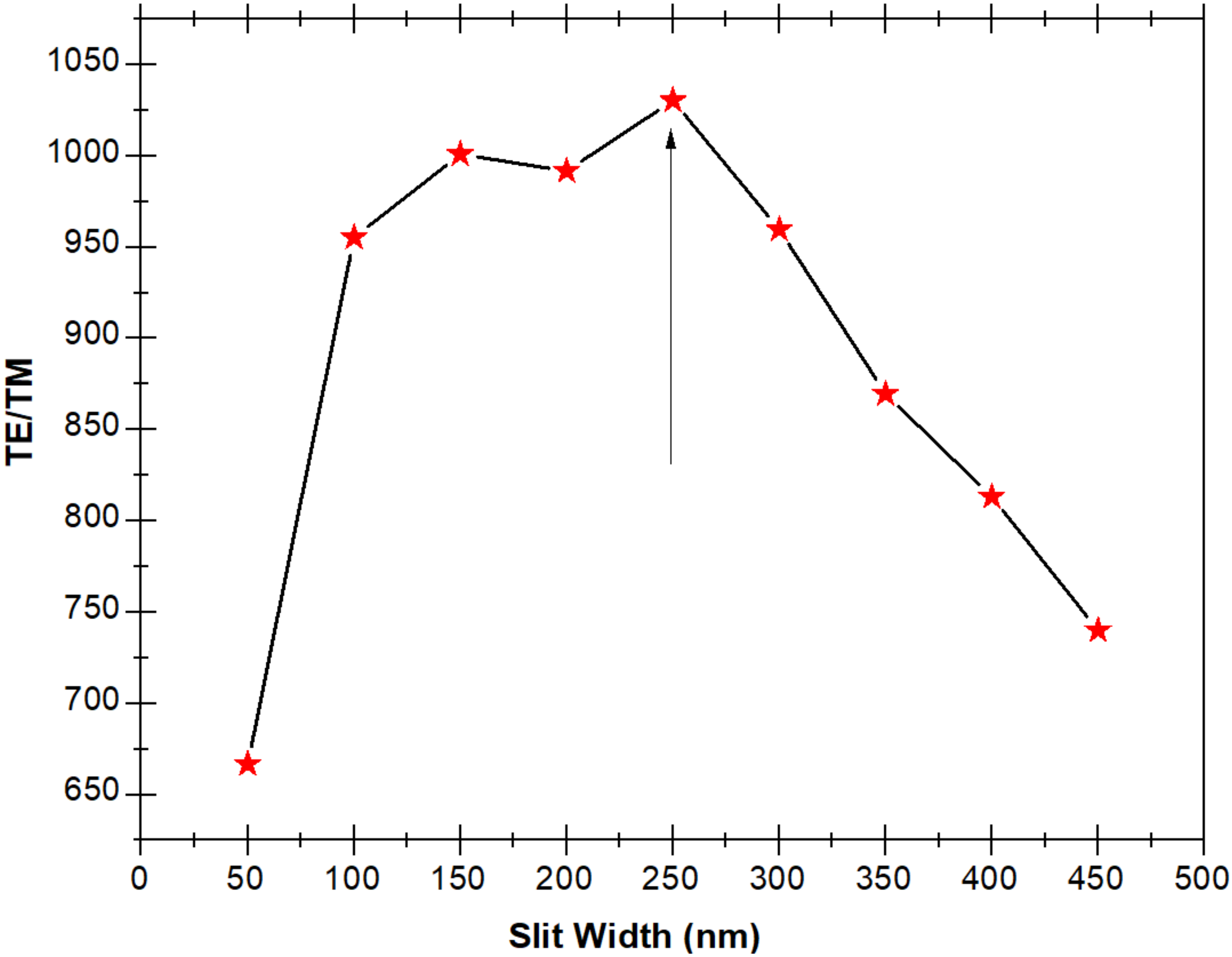

Figure 4

The plot of EOT calculated at varied slit width. The calculations of TE and have been done from R1 and R2 shown in figure 3.

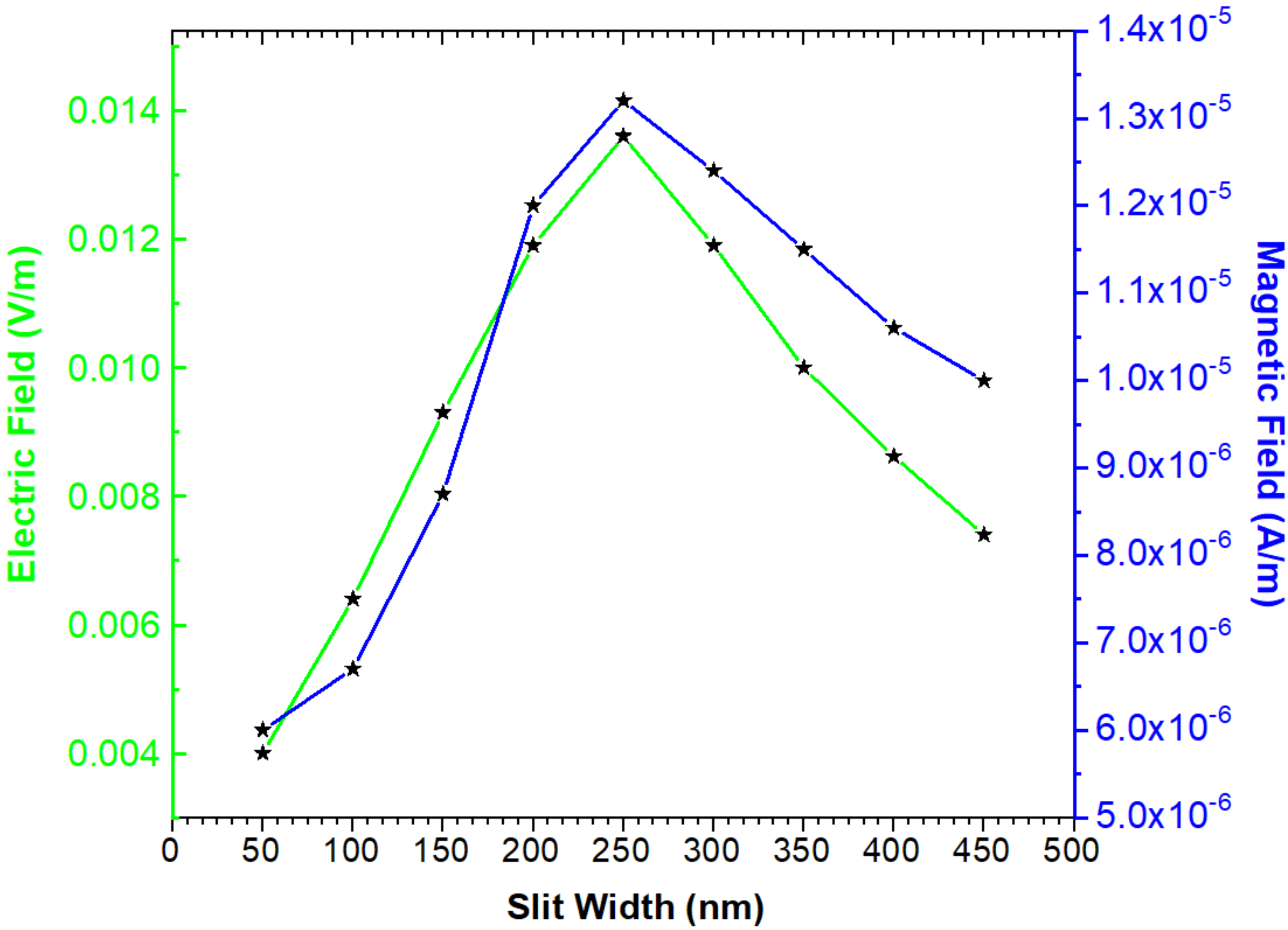

Figure 6

The Near-field analysis of the models with different values of slit width (50-450nm). The maximum field corresponds to the optimum value of slit width.