Photon detection at subwavelength scales

Wang, Q.

Citation

Wang, Q. (2015, October 27). *Photon detection at subwavelength scales*. Retrieved from https://hdl.handle.net/1887/35972

Author: Wang, Qiang
Title: Photon detection at subwavelength scales
Issue Date: 2015-10-27

Chapter 6

Near-Field Single-Photon Detection in a Scattering SNOM

A conical tip made out of good conductive metal can be used to efficiently localize the optical field at the apex of the tip. For a tip of finite length both a field singularity (lightning rod effect) and a surface plasmon resonance contribute to the electric field enhancement. A strongly absorbing superconducting nanodetector placed in the optical near field of the tip shows enhanced optical absorption. The design of an optimal tip-detector system is nontrivial because the strong damping by the detector shifts the resonance wavelength of the tip and significantly lowers the quality factor of the resonance. We compare calculations of the field enhancement of a bare tip to the absorption enhancement in the detector in the presence of the tip as a function of tip length, apex radius and semi-angle of the cone. The resonance of a 225 nm long gold tip in the presence of a nanodetector occurs at ~ 1000 nm and is red-shifted by 150 nm compared to the resonance of a bare tip[1].

---

[1] Q. Wang, and M. J. A. de Dood, proceeding 9504-2, SPIE Optics + Optoelectronics, Prague, Czech Republic, (2015).

6.1 Introduction

Direct detection of single photons in the optical near field would be beneficial to the investigation of light-matter interaction on the nanoscale. However, this involves two contradicting requirements: the detectors should have near-unity efficiency and they should be smaller than the wavelength of light. Nanometer-sized NbN superconducting single-photon detectors (SSPDs) [61] have been applied in quantum optics and communication due to its sensitivity to a wide wavelength range, low noise and a high detection efficiency [17]. Such detectors are prime candidates to be used as a sensor in near-field photon detection [32]. To study the absorption of the detector in the near field, we perform finite-difference-time-domain (FDTD, FullWave package, RSoft [71]) simulations to calculate the enhanced field and photon absorption of the detector in the vicinity of a tip of a scattering scanning near-field optical microscope (scattering SNOM).

We consider a long, 150 nm wide, 5 nm thick NbN wire fabricated on a GaAs substrate. The wire is constricted to a small, 150 nm × 100 nm weak point in the wire [38, 64]. When a current is applied to these nanodetectors the superconductivity is weakest at the constriction and absorption of single photons leads to detection events. By reducing the bias current more photons need to be absorbed at the same time to trigger the detector and the detector thus operates in a higher photon number regime [29, 36]. To increase the near-field absorption of a subwavelength detector an antenna structure that enhances the local field is desirable. We explore the scattering of a gold tip with a finite length. Such tips are used in SNOM experiments and large local field enhancements have been reported [105]. However, it is unknown how strongly this tip interacts with the detector and if the presence of strong absorption in the near field affects, or even destroys the resonant nature of such a tip.

To explore this regime we simulate a sharp metal tip placed above the NbN detector that scatters the incident light to the detector in the optical near field. The sharp tip acts as an antenna or a point-like source, which localizes the light field around its apex. From simulations we find that the absorption of the detector is strongly concentrated and enhanced due to the presence of the tip. This enhancement depends on the wavelength of the incident light, and on the position and geometry of the tip. Here we report the absorption of the detector in a scattering SNOM as a function of the tip geometry and compare this to previous studies of the enhanced local field of the bare tip.

Figure 6.1 shows the detailed geometry of the gold tip and the detector used in the simulation. As shown in Fig. 6.1(a) the tip is modeled as a combination of a cone (semi-angle α and length L) and a hemisphere (radius r) at the end. The origin of the coordinates is set at the apex of the tip. In the simulation, tabulated values of the dielectric constant of gold as a function of wavelength

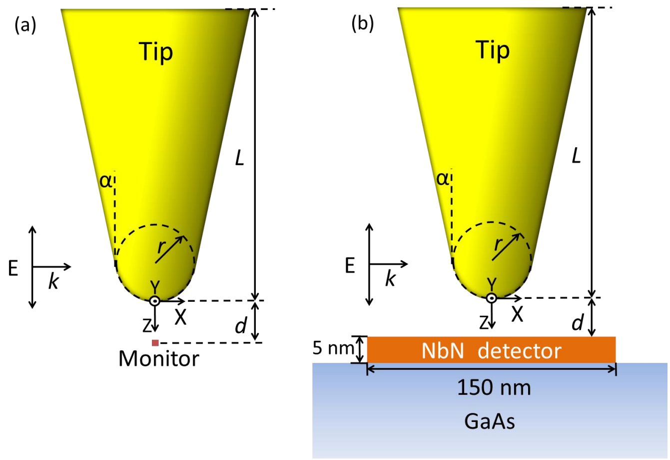

Figure 6.1: Cross section of the 3D model of the bare tip (a) and the tip-nanowire (detector) system (b). (a) The tip has a geometry of a cone with length L and semi-angle α and ends in a semi-sphere of radius r. For the bare tip the electric field is monitored at a position of 5 nm away from the tip apex ($z = 5$ nm). (b) The detector is 150 nm wide and 5 nm thick on a semi-infinite GaAs substrate. The gap d between the tip and the detector is fixed to 5 nm. The polarization of the incident light is parallel to the long axis of the tip.

[71, 106] are used to calculate the optical response of the bare tip. The incident light propagates in a direction perpendicular to the long axis of the tip and is polarized with the electric field parallel to the long axis of the tip, which leads to strong electric field enhancement at the tip apex [99, 107, 108].

Figure 6.1(b) shows the tip-detector system. In order to make the 3D simulations efficient we consider only the constricted point of the NbN nanowire, i.e., the active area of the detector. The nanowire is thus reduced to a 150 nm × 100 nm slab of NbN with a thickness of 5 nm. The underlying GaAs substrate is treated as semi-infinite. To calculate the optical properties of this tip-detector system we use tabulated values of the dielectric constant of the GaAs substrate [71]. The angular frequency dependence of the dielectric constant of NbN is extracted from a Drude model [104]. We use

$$\varepsilon(\omega) = \varepsilon_{high} - \frac{\varepsilon_{high}\omega_p^2}{\omega^2 + i\gamma\omega},$$

where $\omega_p = 5.28 \times 10^{15}$ rad/s is the plasma frequency, $\gamma = 3.77 \times 10^{15}$ rad/s is the damping constant of the plasma excitation, and $\varepsilon_{high} = 12.5$ is the relative permittivity in the high frequency limit.

The influence of the tip geometry is investigated at a reference wavelength of 1000 nm. At this wavelength the complex valued dielectric constant of gold, NbN and the GaAs substrate are $\varepsilon_{Au} = -38.13+3.47i$, $\varepsilon_{NbN} = -15.57+58.62i$ and $\varepsilon_{GaAs} = 12.25$, respectively. As a rule of thumb, the sharp tip serves as an antenna, which localizes the electric field into a limited area within a range of $2r$ from the end of the tip [109]. Therefore, the gap d between the tip and the nanowire is fixed to 5 nm, to place the detector in the area of resonantly enhanced electric field of the tip.

6.2 Wavelength dependence and resonantly enhanced absorption

In a scattering SNOM a good conductive, sharp tip with a radius much smaller than the excitation wavelength functions as an optical antenna, which localizes the electric field and enhances the intensity of the field. Enhancement of $|E|^2$ up to a factor of $\sim 10^3$ was reported [48]. Two mechanisms that localize the electric field can be identified: the local resonance of surface electron oscillation (surface plasmon effect) [48] and the local field increase due to sharp edges and curvatures (lightning rod effect) [49]. Both mechanisms depended on the geometry of the tip in a nontrivial way. In order to understand the more complicated tip-detector system, we start by calculating the enhancement of the electric field around a bare gold tip.

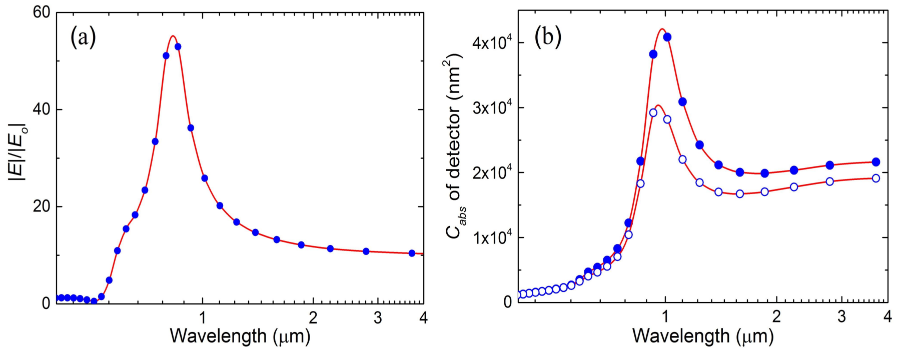

Figure 6.2: Electric field enhancement spectrum for the bare tip (a) and absorption spectrum of the nanowire (b). The dots represent the FDTD simulation results and the red curves serve to guide the eye. For figure (b) the two sets of data represent two settings of gap d: 5 nm (closed symbols) and 10 nm (open symbols).

Figure 6.2(a) shows the electric field enhancement at z = 5 nm below the tip as a function of wavelength of the incident light for a tip with length L = 200 nm, apex radius r = 10 nm and cone semi-angle α = 15°. We define the field enhancement factor F as $|E|/|E_0|$, where E is the modulus of the total electric field in the presence of the tip and $|E_0|$ is the amplitude of the incident electric field. The spectrum is obtained by using a pulsed excitation in the FDTD simulation. We use a pulse with a Gaussian envelope function with a width of 2.67 fs, which multiplies a sinusoidal carrier wave with a center wavelength of 800 nm. The enhancement factor shows a main resonant peak at wavelength of $\sim$ 850 nm and a small feature at $\sim$ 650 nm. The peak originates from the surface plasmonic resonance, for which the electrons are driven by the electric field parallel to the z axis. We attribute the feature at 650 nm to a higher (second) order of this resonance mode, which has a shorter resonant wavelength [44].

Figure 6.2(b) shows the absorption of the nanowire in the presence of the tip as a function of wavelength. The geometry of the tip is identical to the one used in the calculation of Fig. 6.2(a). A resonance in the absorption of the nanowire is observed that resembles the field enhancement of the bare tip. We attribute this enhanced absorption to the plasmonic resonance of the tip that is damped by the detector. This damping becomes apparent when comparing the data in Figs. 6.2(a) and 6.2(b). The resonant wavelength of the bare tip is close to 850 nm, while the resonance in the presence of the detector is red-shifted to $\sim$ 1000 nm. This redshift is partly due to the presence of the high-index substrate and partly due to the detector that acts as a resistive load and damps the antenna (tip) resonance [110, 111]. The loading effect of the detector is calculated for a distance $d = 5$ nm (closed symbols in Fig. 6.2(b)) and $d = 10$ nm (open symbols in Fig. 6.2(b)).

To further analyze the two sets of data in Fig. 6.2(b), we determine the peak wavelength λ_0. The lack of a description of the background absorption makes it difficult to extract parameters other than the peak wavelength of the resonance in an unambiguous way. For the two gap settings we find $\lambda_0 = 975 \pm 5$ nm for $d = 5$ nm and $\lambda_0 = 950 \pm 5$ nm for $d = 10$ nm, where the estimated error bars represents an estimate of the error due to the varying background. Following the discussion above, the larger gap of 10 nm should result in an antenna (tip) with a smaller load, and gives a smaller redshift compared the the system of $d = 5$ nm. This is consistent with the calculation presented in Fig. 6.2(b).

6.3 Electric field enhancement by the bare tip

In order to study the influence of the geometry of the tip on the enhancement factor, we simulated the tip with excitation of a Gaussian beam at a single wavelength of 1000 nm. The effect of these geometrical parameters on the tip resonance and field-enhancement is well-known. We reproduce these results here for completeness and to obtain a reference for the more complicated geometry of the tip-detector system.

Figure 6.3 shows the enhancement factor as a function of tip length L, apex

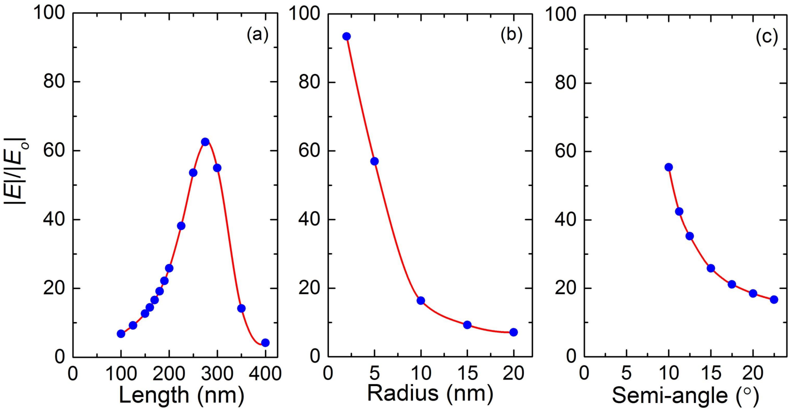

Figure 6.3: Electric field enhancement at a wavelength of 1000 nm in the near field as a function of tip geometry. (a) The enhancement factor is calculated at $z = 5$ nm with a resonance peak at $L \approx 275$ nm for fixed values of the tip radius $r = 10$ nm and semi-angle $\alpha = 15°$. (b) The data points of the enhancement factor as a function of radius are obtained at the position of $z = r$ for fixed values of the tip length $L = 200$ nm and semi-angle $\alpha = 15°$. (c) The enhancement factor as a function of semi-angle is calculated at the position of $z = 5$ nm for fixed values of the tip radius $r = 10$ nm and length $L = 200$ nm.

radius r and semi-angle α. The resonance of the surface plasmon is determined primarily by the tip length L, and with incident light at 1000 nm the resonance occurs at $L \approx 275$ nm.

Since the electric field is mainly concentrated in a range of $2r$ around the tip, we monitor the electric field at the position of $z = r$. The influence of the apex radius r is shown in Fig. 6.3(b) and a monotonic decrease of the enhancement factor with the radius of the tip is observed. The radius r of the rounded tip has minimal influence on the plasmonic resonance, but strongly influences the lighting rod effect that is related to a field singularity at the apex of an infinitely sharp tip. For a finite apex radius, the charge density at the apex is reduced for larger values of r due to the increased area of the tip apex. Therefore the electric potential is lowered and the electric field at the tip becomes weaker.

The influence of the semi-angle α is reported in Fig. 6.3(c) and shows that the enhancement of the electric field decreases with semi-angle. This effect is well understood and can be explained by a simple model of a sharp cone, around which the electric field is $E(z) \propto z^{\nu-1}$, where ν is between 0 and 1 and is determined by the semi-angle [112]. The exponent ν increases for large semi-angles, which results in slower field decay and smaller enhancement factor.

6.4 Absorption of the nanowire with the tip

The tip geometry-dependent absorption cross section of the nanowire is calculated in a similar way as the enhancement factor at a wavelength of 1000 nm. Figure 6.4 shows the absorption as a function of length L, radius r and semi-angle α. The absorption with the tip is higher than that without tip (dashed line) due to the enhanced local electric field. The influence of the geometry of the tip is reported in the three subfigures and is qualitatively similar to the behavior for a bare tip. We interpret this result in the sense that the same mechanisms of electric field enhancement of the bare tip are responsible for the absorption enhancement despite the strong damping induced by the detector.

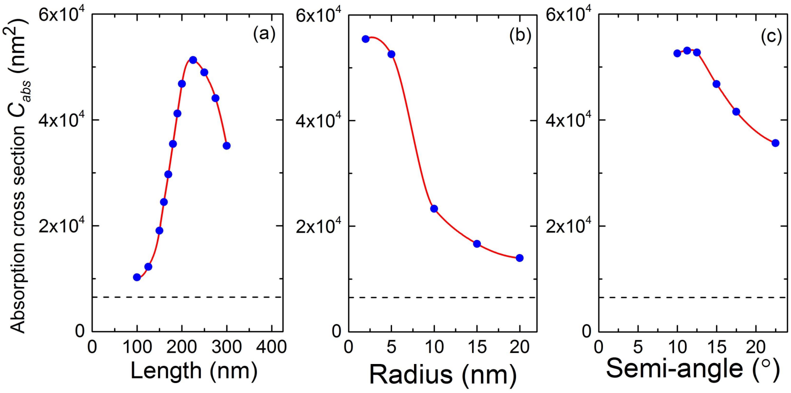

Figure 6.4: Absorption cross section of the nanowire as a function of the geometry of the tip at a wavelength of 1000 nm. The dashed line is the absorption cross section without the tip as a reference. (a) The absorption cross section is calculated at $z = 5$ nm with a resonance peak ($L = \sim 225$ nm) with $\alpha = 15°$ and $r = 10$ nm. (b) The data points are obtained at position $z = r$ to make sure most of the nanowire is in the area of the enhanced electric field. Other settings of geometry are set to $\alpha = 15°$ and $L = 200$ nm.(c) The absorption cross section is calculated at the position of $z = 5$ nm as a function of semi-angle with $r = 10$ nm and $L = 200$ nm.

Figure 6.4(a) shows that the resonance occurs for a length $L = 225$ nm for the loaded tip compared to $L = 275$ nm for the bare tip. We explain this shift in tip length by a phase-shift in the amplitude reflection coefficient of the tip due to the resistive load of the detector. As a result the resonance has a lower quality factor and occurs in a shorter length antenna. For Figs. 6.4(b) and 6.4(c) we stress that the absorption (cross section) of the nanowire is proportional to the integral of $|E|^2$ over the whole nanowire, and this integral over a relative larger region (nanowire) varies more slowly than the electric field in a single point on the z axis. Hence, Figs. 6.4(b) and 6.4(c) show a smooth change (especially at small radii and semi-angles) instead of the strong dependence in Figs. 6.3(b) and 6.3(c).

6.5 Conclusions

We have calculated the electric field enhancement around a sharp, conical, gold tip illuminated by a plane wave from the side. The strong field enhancement of a bare tip originates from surface plasmon resonance and lightning rod effect. The resonant wavelength of the field enhancement is mainly determined by the length of the tip, and depends strongly on the apex radius and cone semi-angle. The enhancement becomes smaller when the radius or semi-angle of the tip increases because the lightning rod effect related to a field singularity at the tip apex is strongly reduced. When a NbN nanodetector is placed in the near-field region of strongly enhanced field we observe that the absorption of light by the nanodetector is resonantly enhanced. At the same time strong shifts in the resonance wavelength (up to 10%) are observed due to the strong resistive load on the tip. Despite the strong damping the absorption of the nanodetector as a function of tip geometry is very similar to the trends observed in the field enhancement of a bare tip. The bare tip can thus be used as a starting point for the design of enhanced near-field detection of single photons. Improvements to the simple description of the bare tip are expected if the model takes into account that the nanodetector acts as a resistive load on the antenna (tip) and that it damps the radiation of the tip.