Coupling light to periodic nanostructures

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Chapter 9

The perfect absorber

We demonstrate that films of very lossy metal or dielectric, with a thickness of only a few nanometers, can absorb almost all incident radiation, when illuminated from the substrate side, at the critical angle for total internal reflection. The absorption for *s*-polarized light approaches 100%, while the absorption for *p*-polarized light vanishes. We demonstrate this effect by measuring the absorption as a function of the angle of incidence, at a wavelength of 775 nm in a 4.5 nm thick NbN film with a dielectric constant $\epsilon_{\mathrm{NbN}} = -8.2 + 31.4i$. The measured absorption in this film reaches a maximum of 94%. We discuss the design of a near-unity efficiency single-photon detector for *s*-polarized light, that has a broadband absorption coefficient of $> 90\%$ for wavelengths from 700 to 1600 nm.

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9.1 Introduction

An ideal photodetector or photovoltaic cell would absorb all incident radiation over a broad range of frequencies, and converts the energy into an electrical signal. Not only should the material absorb all radiation, it should also be thin enough to efficiently collect the electrical signal. Although very desirable, these requirements seem contradictory, and thin film materials that absorb all incoming light are extremely hard to find. A possible route around this problem is to use conventional materials and couple resonantly to a surface polariton [56, 105, 106], a waveguide mode [107], or a cavity that incorporates the absorbing material [85, 89]. Unfortunately, the resonant nature of these effects implies that the absorption can only be large over a narrow range of frequencies.

More recently, transition edge sensors [108] and high speed superconducting single-photon detectors (SSPDs) [79] have been described that use thin layers of extremely lossy materials, i.e. materials with a very large complex part of the dielectric constant. For these devices, the absorption is limited due to a large impedance mismatch at the interface, and the absorption at normal incidence is limited to 50% when the film is illuminated from the air side [79,85]. Illumination from the substrate side decreases the impedance mismatch and increases the optical absorption in the film by a factor n_{s}, where n_{s} is the refractive index of the substrate [109].

In this chapter, we show that it is possible to reach almost 100% absorption in a lossy film of only a few nanometers thick if the film is illuminated by *s*-polarized light at the critical angle for total internal reflection. We show measurements on the polarization-dependent absorption of an unstructured 4.5 nm thick NbN film on a sapphire substrate, and find that the absorption is well above 90%. The same concept can be applied to a detector structure that consists of a subwavelength meandering NbN wire. Calculations show that the absorption reaches a maximum of 94% when the detector is illuminated at the critical angle, and is $> 90\%$ over a wide frequency range.

9.2 Absorption of a closed film

In order to measure the absorption of a thin, lossy film at the critical angle, we used a 4.5 nm thick NbN film deposited on a double-polished R-plane sapphire substrate ($n_{\mathrm{s}} = 1.75$). The substrate was placed on an isosceles BK7 prism ($n = 1.51$) with index matching liquid between the substrate and the prism. This allows us to illuminate the film at angles larger than the critical angle for

total internal reflection [110].

Figure 9.1 shows the measured absorption of a 4.5 nm thick NbN film, at a wavelength of 775 nm, as a function of the angle of incidence, for light polarized parallel to the interface (s-polarized, closed symbols) and light with an electric field component perpendicular to the interface (p-polarized, open symbols). The film was illuminated using a 775 nm continuous-wave diode laser that was collimated to a $\sim$ 1 mm diameter beam. The polarization and orientation of the birefringent substrate were set to ensure that the linear polarization of the incident radiation was unchanged. The transmitted (T) and reflected (R) fraction of the incident power were recorded as a function of angle of incidence using a silicon photodiode, and were corrected for the losses due to reflections at the prism-air interfaces. From this the absorption is obtained as $A = 1 - R - T$.

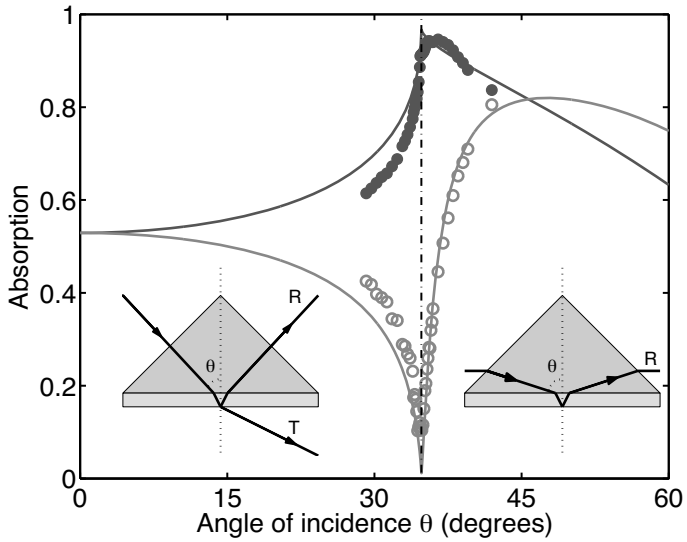

Figure 9.1. Measured optical absorption of a 4.5 nm thick NbN film as a function of angle of incidence, for s- (closed symbols) and p- (open symbols) polarized light. The curves are a fit of Fresnel's equations, using the (complex) refractive index of the NbN as only fit parameter. The dash-dotted line indicates the critical angle for total internal reflection. The insets show the experimental configuration of the prism and the substrate.

The dash-dotted line in Fig. 9.1 indicates the critical angle $\theta_c = \arcsin(n_s^{-1})$ for the substrate. For angles larger than this angle, light is not allowed to propagate in the air, and all incident light is either reflected or absorbed. At

the critical angle, the absorption for s-polarized light goes to a maximum value of $\sim 94\%$, for a film that is only 4.5 nm thick. At the same angle, the absorption for p-polarized light goes to a minimum of $\sim 10\%$.

At the critical angle θ_c, the amplitude of the evanescent wave extending into the air is zero. Hence, all the fields are contained in the half space bounded by the metal-air interface. For p-polarized light, the reflected and incident wave are out of phase, which creates an antinode in the thin film, expelling the field from the absorbing medium. For s-polarized light, the reflected and incident waves are in phase, creating a node at the boundary. A large part of the field is thus contained in the absorbing film, and absorbed.

We stress that the high absorption is not caused by coupling to a surface plasmon resonance or another polaritonic excitation on the metal-air interface. Such resonances only occur for p-polarized light (open symbols), at angles beyond the critical angle [105]. In fact, the local maximum for p-polarized light at an angle of incidence $\theta \approx 55^\circ$ is a remnant of the surface plasmon. Since we are dealing with a very thin, very lossy metal film, there is no sharp resonance. It is interesting to note that, at an angle $\theta \approx 46^\circ$, the absorption for both s- and p-polarized light can be as high as 80%.

We compare the measured absorption to the absorption calculated using Fresnel's coefficients for the reflection and transmission of a system with two interfaces [43]. The curves in Fig. 2.6 show a fit to the measurements where we used the complex dielectric constant of the absorbing NbN layer as the only fit parameter, giving $\epsilon_{\text{film}} = -8.2 + 31.4i$. We attribute the differences between the fit and the measurements to a small residual polarization rotation caused by the birefringence of the sapphire substrate.

The film thickness and the dielectric constant of the film determine the value of the absorption at the critical angle. For a film thickness much smaller than the wavelength, interference can be ignored. Furthermore, for a very lossy material, the real part of the dielectric constant of the film can be neglected. The absorption for s-polarization can then be approximated as [102]

$$A \approx 4 \frac{\sqrt{n_{\text{s}}^2 - 1}\, k_0 d \,\text{Im}\, \epsilon_{\text{film}}}{\left(\sqrt{n_{\text{s}}^2 - 1} + k_0 d \,\text{Im}\, \epsilon_{\text{film}}\right)^2}, \tag{9.1}$$

where k_0 is the wave vector of the light in vacuo, and d is the film thickness. The absorption reaches a maximum value at a film thickness given by

$$d = \frac{\sqrt{n_{\text{s}}^2 - 1}}{k_0 \,\text{Im}\, \epsilon_{\text{film}}}. \tag{9.2}$$

Note that the real part of the dielectric constant, and therefore also the sign of the real part, does not enter the expression for the maximum in absorption. This means that the maximum in absorption should occur both for lossy dielectrics and for lossy metals.

9.3 Nanostructured films

Some applications of thin absorbing films actually require a non-uniform film in order to work. In the remainder of this paper, we will show that it is equally possible to obtain the near-unity absorption for a superconducting single-photon detector [79], that consists of a meandering NbN wire. Absorption of a photon in this superconducting wire provides enough energy to give rise to a finite voltage pulse, which can be detected to count single photons. The parallel wire grid structure of the detector makes that light polarized parallel to the wires has a higher probability of being absorbed [85, 109].

Figure 9.2 shows the calculated absorption for a detector structure using the rigorous coupled-wave analysis developed in Ref. [37], as a function of angle of incidence, for light polarized parallel (TE) or perpendicular (TM) to the wires. The detector was oriented such, that the TE direction was parallel to the *s*-polarization of the incident light. This choice of orientation allows us to combine the high absorption due to the polarization dependence induced by the periodic grating structure, with the maximum in absorption due to the illumination at the critical angle. The detector has a line width of 100 nm and a filling factor of $f = 50\%$, and the thickness of the NbN lines was set to $d = 11.3$ nm to maximize the absorption. The value of the thickness was obtained from Eq. (9.2), taking an effective dielectric constant [95] for the patterned layer of $\epsilon_{\text{film}} = f + (1-f)\epsilon_{\text{NbN}}$, where ϵ_{NbN} is the dielectric constant of NbN.

At the critical angle, the calculated absorption reaches a maximum value of 94%, for *s*-polarized light. This confirms the fact, that the finite filling factor can be countered by increasing the film thickness [109]. It is important to notice that for an angular spread of $\sim 10^\circ$ around the critical angle, the absorption is still well above 80%, making the proposed detector also efficient for absorbing light with a finite numerical aperture.

In Fig. 9.3, we show the variation of the absorption of the detector geometry defined before, as a function of the film thickness, calculated using the rigorous coupled-wave analysis, for both polarizations. The graph shows that the absorption for *s*-polarized light reaches a maximum at $d = 10.8$ nm, close to the value predicted from Eq. (9.2). From this figure, we conclude that for

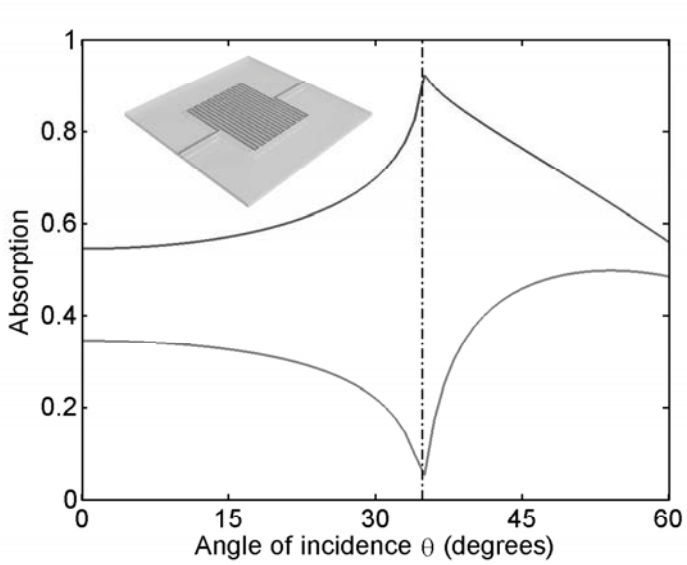

Figure 9.2. Calculated absorption as a function of the angle of incidence, for a detector geometry having a lattice period of 200 nm and a filling factor of 50% (as shown in the inset). The top curve gives the absorption for s-polarized light, the bottom curve for p-polarized light. The lines of the detector are positioned such that they are parallel to the p-polarization. The thickness of the detector layer $d = 11.3$ nm was set for optimal absorption. The dash-dotted line indicates the critical angle.

detectors with a thickness between 7 nm and 20 nm, the absorption is still $> 80\%$. This is much higher than the value obtained by other methods [89] and comparable to the optimum efficiency of silicon avalanche photodiodes. It also shows that the maximum in absorption is not very sensitive to the design of the detector. Decreasing the thickness might give rise to an increased electronic conversion efficiency for this kind of detectors [104]. This decrease in film thickness can be countered by an equal increase in filling factor f.

The inset of Fig. 9.3 shows the calculated wavelength dependence of the absorption. For this calculation, we used literature values for the dispersion of the sapphire substrate [97] and a Drude model for the dielectric constant of the NbN material [98]. We changed the high-frequency dielectric constant and the loss parameter to adjust the Drude model to the dielectric constant of the NbN film at 775 nm. The angle of incidence was set at the critical angle for a wavelength of 775 nm. The calculated absorption is almost constant.

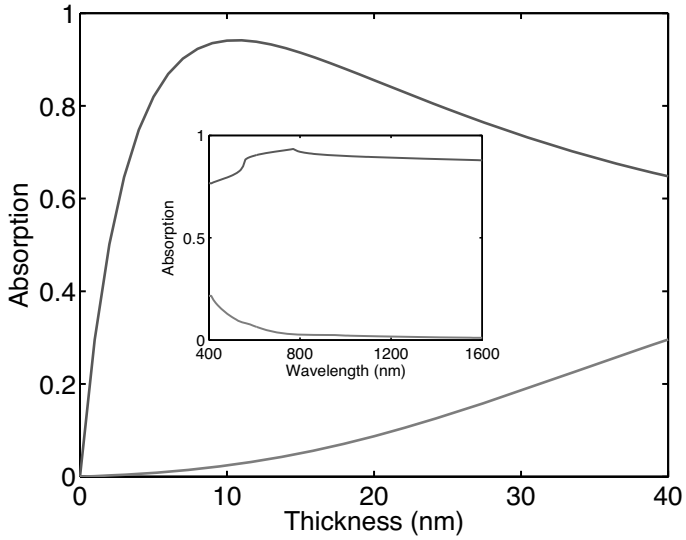

Figure 9.3. Calculated dependence of the absorption on the thickness of the NbN detector. For *s*-polarized light, the absorption has a maximum of 94.5% around 10.8 nm thickness. The inset shows the absorption as a function of the wavelength of the incident light. The wavelength dependence is small for *s*-polarized light.

This is due to the fact that the maximum absorption is only dependent on the product k_0 Im ϵ, which is nearly constant for a Drude metal far from resonance. As a result, the optimal film thickness only varies marginally with the wavelength of the incident light. The decrease in absorption at wavelengths < 550 nm is caused by the fact that for these wavelengths, diffraction from the periodic structure decreases the overall absorption. The dispersion of the sapphire substrate causes the small feature at 775 nm. At this wavelength, the angle of incidence is set exactly at the critical angle, and the absorption is maximal. For wavelengths below (above) this value, the angle is slightly below (above) the critical angle.

9.4 Conclusions

In conclusion, we have shown experimentally that the optical absorption of a 4.5 nm thick NbN can reach values as high as 94% for *s*-polarized light incident from the substrate side, at the critical angle for total internal reflection. For a very lossy material, the absorption of a thin layer does not depend on

the real part of the dielectric constant. The concept described here can therefore be applied to all devices that rely on the absorption of light in a thin, strongly absorbing film. To demonstrate this, we proposed a design for a superconducting single-photon detector that takes advantage of this effect, and calculated that this detector can reach an absorption efficiency as high as 94% for a filling factor of only 50%. The calculated absorption of the detector is shown to be almost wavelength-independent, and robust against changes in film thickness. At the critical angle, the light that is not absorbed is reflected and can be collected by a second detector. This way, a high-speed, near-100% single-photon detector comes into reach that might be competitive with existing silicon avalanche photodiodes in the visible. Since the effect is to a large extent wavelength independent, similar detector performance can be reached at telecommunication and infrared wavelengths were no fast single photon detectors with high ($> 50\%$) efficiency exist. To apply our method to photovoltaic cells or photodiodes requires a semiconductor material with $\mathrm{Im}\ \epsilon \ll \mathrm{Re}\ \epsilon$, which may be achieved by an appropriately designed metamaterial.