Perfect absorption in thin NbN films

E. F. C. Driessen[1] and M. J. A. de Dood [1]

[1] Huygens Laboratory, Leiden Universtiy, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands

We demonstrate that a thin film of a very lossy material can absorb almost all light when illuminated from the substrate side at the critical angle for total internal reflection. The absorption for s-polarization approaches 100%, while the absorption for p-polarization vanishes. We measured the absorption, at a wavelength of 775 nm, as a function of angle of incidence for a 4.5 nm thick NbN film, and find a maximum absorption of 94%. We discuss the design of a near-unity efficiency single-photon detector for s-polarized light with an absorption coefficient of >90% for wavelengths from 700 to 1600 nm.

Introduction

An ideal photodetector absorbs all incident radiation over a broad range of frequencies and converts the energy into an electrical signal. To collect the electrical signal efficiently this absorption should be achieved in a thin film, leading to seemingly contradicting requirements. A common proposal is to couple resonantly to a surface polariton, [1–3], a waveguide mode, [4] or a cavity that incorporates the absorbing material. [5,6]. The resonant nature of these effects necessarily implies that these devices will work in a narrow frequency band.

More recently, superconducting single-photon detectors (SSPDs) [7] have been described that use a thin layer of extremely lossy NbN material. For these devices, the absorption is limited due to a large impedance mismatch at the interface, and the maximum possible absorption at normal incidence is 50% when the film is illuminated from the air side [6,8]. Illumination from the substrate side decreases the impedance mismatch and increases the optical absorption in the film by a factor equal to the refractive index of the substrate [8].

As we will show, it is possible to reach significantly larger 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 measure 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% for a non-optimized geometry.

Superconducting single-photon detectors

Superconducting single-photon detectors (SSPDs) consist of a meandering NbN wire, and are interesting because of their relatively high quantum efficiency at infrared wavelengths, low time jitter, low dark counts, and high counting rates [9]. On a macroscopic level, a photon that is absorbed by the superconducting wire triggers a temporary loss of superconductivity, which gives rise to a finite voltage pulse across the detector. Thus, the optical absorption efficiency plays a key role and is primarily determined by the geometry of the detector and the dielectric constant of the NbN layer.

In this article, we focus on the optical absorption of a 4.5 nm thin NbN film and show how the absorption can be increased beyond 90% by illuminating the film from the substrate side [10]. Although we consider a closed film at room temperature our results are equally valid for a detector operating at room temperature. Since the energy of the incident photons is much larger than the superconducting gap of the NbN, the complex dielectric constant of the NbN layer at room temperature can be used [11]. The microstructure of sub-wavelength parallel wires induces a strong polarization dependence, that can be modelled by an effective dielectric constant [6,8]. An alternative solution is to change the design of the detector to a geometry with a spiralling wire [12].

Perfect Absorption

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 (ns =1.72). The substrate was placed on an isosceles BK7 prism (n =1.51) with index matching liquid between the substrate and the prism. The prism allows illumination of the film at angles larger than the critical angle for total internal reflection. The film was illuminated using a 775 nm continuous-wave diode laser that was collimated to a ~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.

We measured the reflection and transmission, at a wavelength of 775 nm, as a function of angle of incidence for both *s* and *p*-polarized light. From these measurements we deduce the absorption of the 4.5 nm thick NbN film. Figure 1 shows the experimentally obtained absorption as a function of angle of incidence at the NbN-to-sapphire interface, for *s*- (open symbols) and *p*-polarized light (filled symbols). The absorption for *s*-polarization reaches a maximum of 94% at the critical angle for total internal reflection, θ = arcsin$(1/n_s)$, while the absorption for *p*-polarized light reaches a minumum close to 10%.

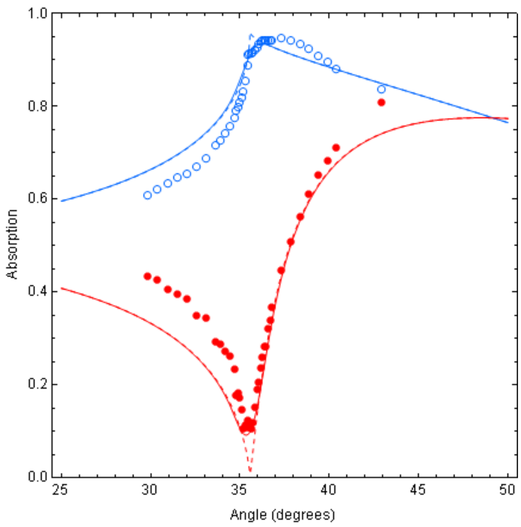

Figure 1: Measured optical absorption of a 4.5 nm thick NbN film as a function of angle of incidence for *s*-(open symbols) and *p*-polarized light (solid symbols). The curves are the calculated absorbtion for a film with a complex dielectric constant ε = −8.2+31.4i.

The dashed lines in Fig. 1 correspond to the calculated absorption for plane-wave illumination, using the Fresnel coefficients of a layered system [13]. To get a good description of the experimental data we use a dielectric constant of −8.2+31.4i for the NbN material. The solid lines in Fig. 1, are theoretical curves that take into account a finite angular spread of the beam. The effect of this angular spread of the incoming beam is most pronounced at the minimum absorption for p-polarized light. An angular spread of ~0.5 degree (NA < 0.01) is sufficient to increase the theoretical absorption for *p*-polarized light from 0% to 10%. The theoretical maximum for *s*-polarized light is reduced from 96% to 92%.

Origin of perfect absorption

The essential feature that enables near 100% absorption in a thin NbN film is its rather peculiar dielectric constant that is dominated by the imaginary part. To better understand the absorption of such a film we evaluated the geometrical series that gives the reflection of the thin film system at the critical angle. For *p*-polarized light, the Fresnel coefficient for reflection from NbN to air is equal to -1. The contribution from the multiple reflections inside the NbN film cancel and the reflection is dominated by the initial reflection from the sapphire-NbN interface, giving a large reflection and consequently a very small absorption due to the large index mismatch between NbN and sapphire.

This situation is very different for *s*-polarized light. The Fresnel reflection coefficient of the sapphire-NbN interface is large, but the Fresnel reflection coefficient for the NbN-air interface is equal to +1 in this case. Therefore, the multiple reflections inside the NbN film do not cancel and lead to a wave with an amplitude that is similar to the first reflection of the sapphire-NbN interface. These two contributions are out of phase and lead to destructive interference for the reflected wave. All light is absorbed in this case, since the amplitude of the transmitted wave is necessarily zero at the critical angle.

This situation is reminiscent of anti-reflection coating that can be made using a thin metal film [14]. This is illustrated in Fig. 2, which shows the calculated reflection, transmission and absorption (at normal incidence) of a thin NbN film on a sapphire substrate as a function of layer thickness for illumination from the air (fig. a) and the substrate (fig. b) side. As can be seen, the absorption (dotted lines) is larger when the film is illuminated through the substrate. The transmission (solid lines) is independent of the illumination, while the reflection (dashed lines) becomes zero for a NbN film of ~3 nm thickness. In this case, the directly reflected and the multiply reflected beam inside the NbN film are out of phase leading to destructive interference in reflection.

At normal incidence the optimum thickness for absorption of 11.5 nm is much larger than the anti-reflection condition. However, when the angle of incidence is varies, as shown in Fig. 2c, the optimum thickness for maximum absorption becomes smaller (solid line in fig. 2c) while the thickness for a minimum in the reflection for *s*-polarized light becomes larger (dashed line in fig. 2c). At an angle of 90 degrees in air, corresponding to the critical angle, the conditions for maximum absorption and anti-reflection coating are the same.

As a final note, we would like to emphasize that the same principles can be applied to working NbN superconducting single photon detectors by optimizing their

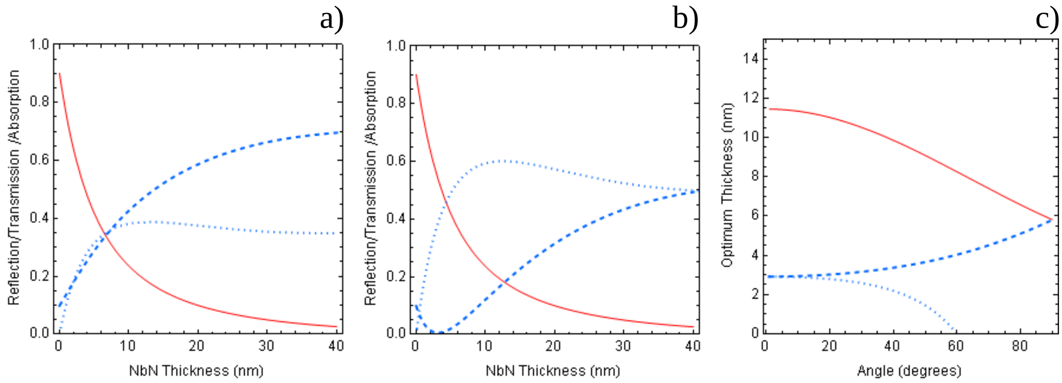

Figure 2: Calculated absorption, reflection and transmission (a,b) for a NbN film with a complex dielectric constant ε = −8.2+31.4i on a sapphire substrate, as a function of thickness. Calculations are shown for normal incidence for illumination from the air side (fig. a) and substrate side (fig. b). The transmission (solid line) is independent of the illumination, while the reflection (dashed lines) and absorption (dotted lines) depend strongly on the illumination side. Figure c shows the optimum thickness of the NbN as a function of angle of incidence (defined in air) for maximum absorption (solid lines) and minimum reflection (dashed and dotted lines) when illuminated through the substrate.

design. Also in this case near 100% absorption can be achieved when illuminating the detector from the substrate side at the critical angle [10].

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