Infrared refractive index measurement of Niobium Nitride thin-film via FTIR

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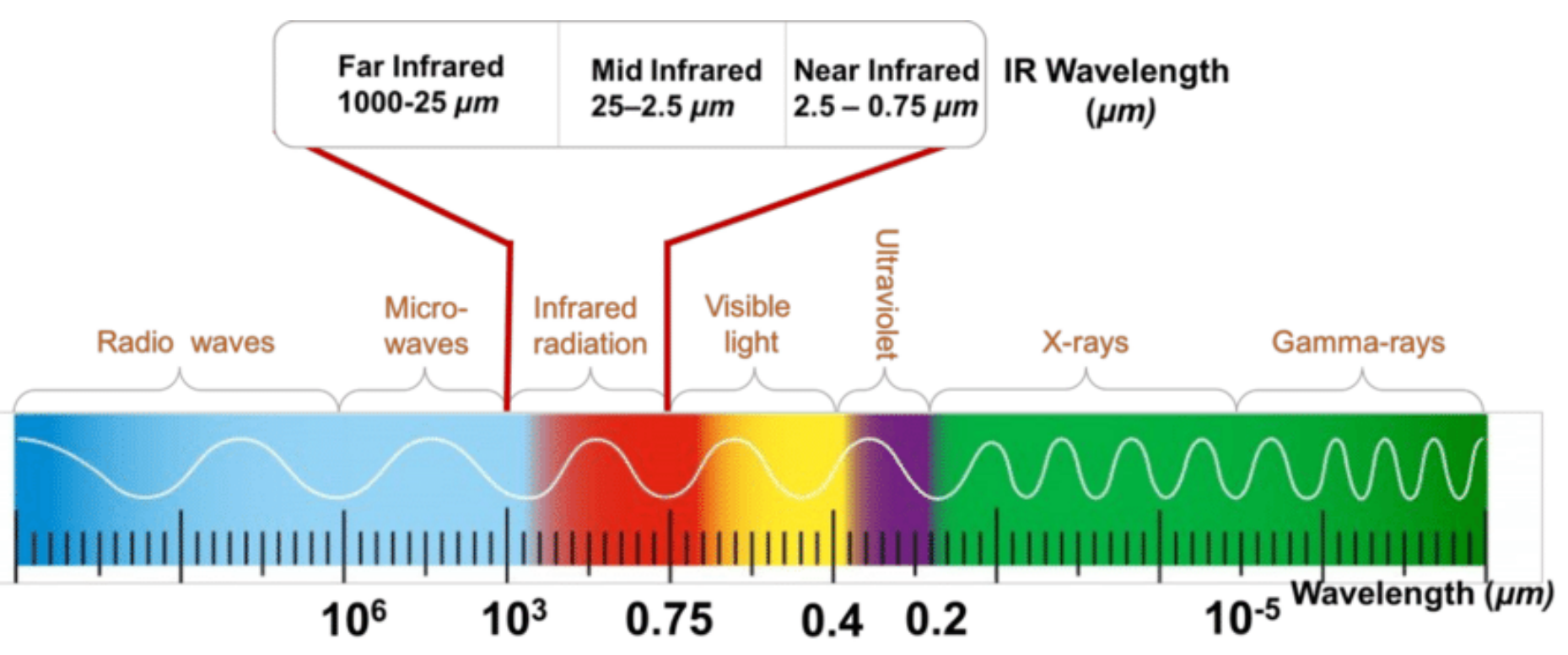
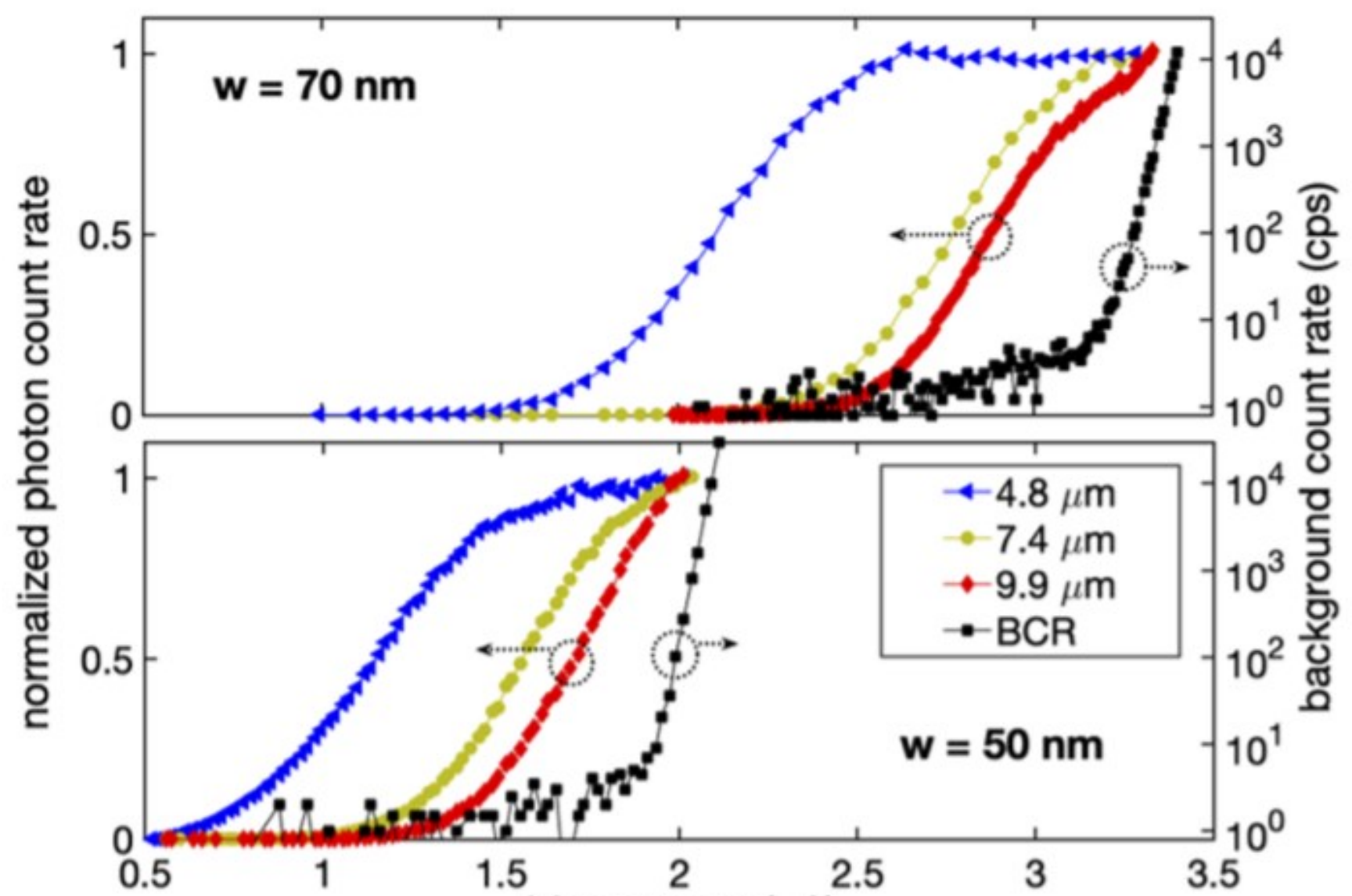
Objective

- Develop an algorithm to extract the complex refractive index of materials in mid-IR wavelength from FTIR reflectance and transmittance spectra
- Calculate the optical constants of thin-film NbN in the wavelength range of 2.5 to 25 μm

Motivation

- Refractive index of material is required for photonic design optimization
- NbN is commonly used for fabricating superconducting nanowire single photon detectors (SNSPDs)
- Mid-IR and long-IR absorption efficiency of SNSPDs is very low [1]
- Refractive index of NbN has been reported in 0.3 – 2.2 μm wavelength [2]
- Accurate refractive index data of superconducting films will help to design better detectors in infrared wavelength





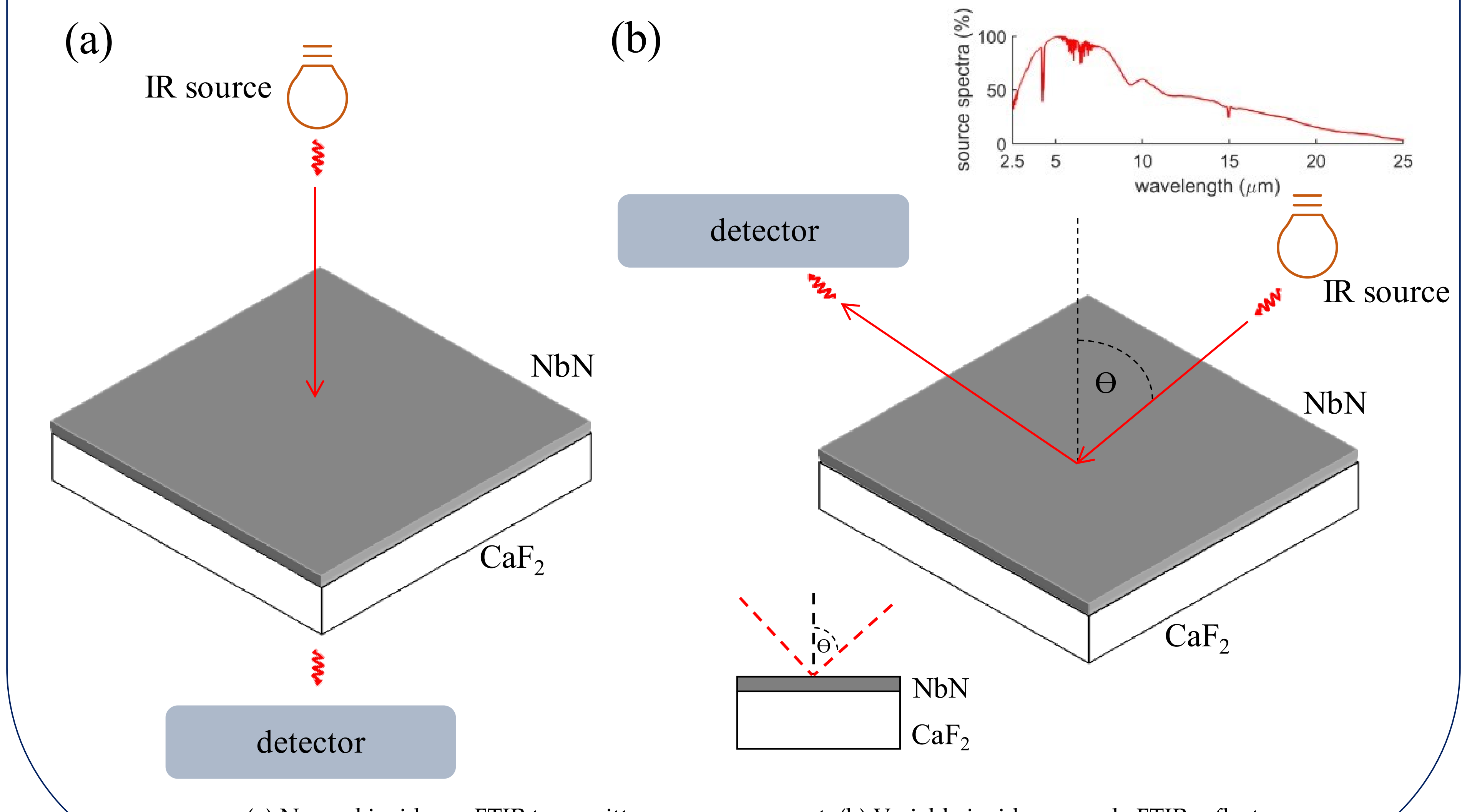
Source: V. Verma et al., APL Photonics, vol. 6, no. 5, p. 056101, 2021

Thin-film deposition

- NbN is deposited on CaF_2 substrate at room temperature using sputtering [3]
- CaF_2 is optically transparent in near- and mid-infrared [4]
- NbN thickness was measured to be 10 nm using XRR
- NbN sheet resistance was 240.68 Ω/sq
- Sputtered films were kept in inert atmosphere to minimize oxidation

FTIR spectra measurement

- Thermo Scientific Nicolet iS50 FTIR spectrometer was used
- Measurements were performed with unpolarized collimated beam
- 64 scans per measurement with automatic atmospheric suppression enabled
- Reflected spectra of sample are normalized by reflected spectra of gold mirror
- Source spectra are used to normalize sample's transmitted spectra
- Pike VeeMAX III reflection accessory was used for incidence angles of 12° to 60°

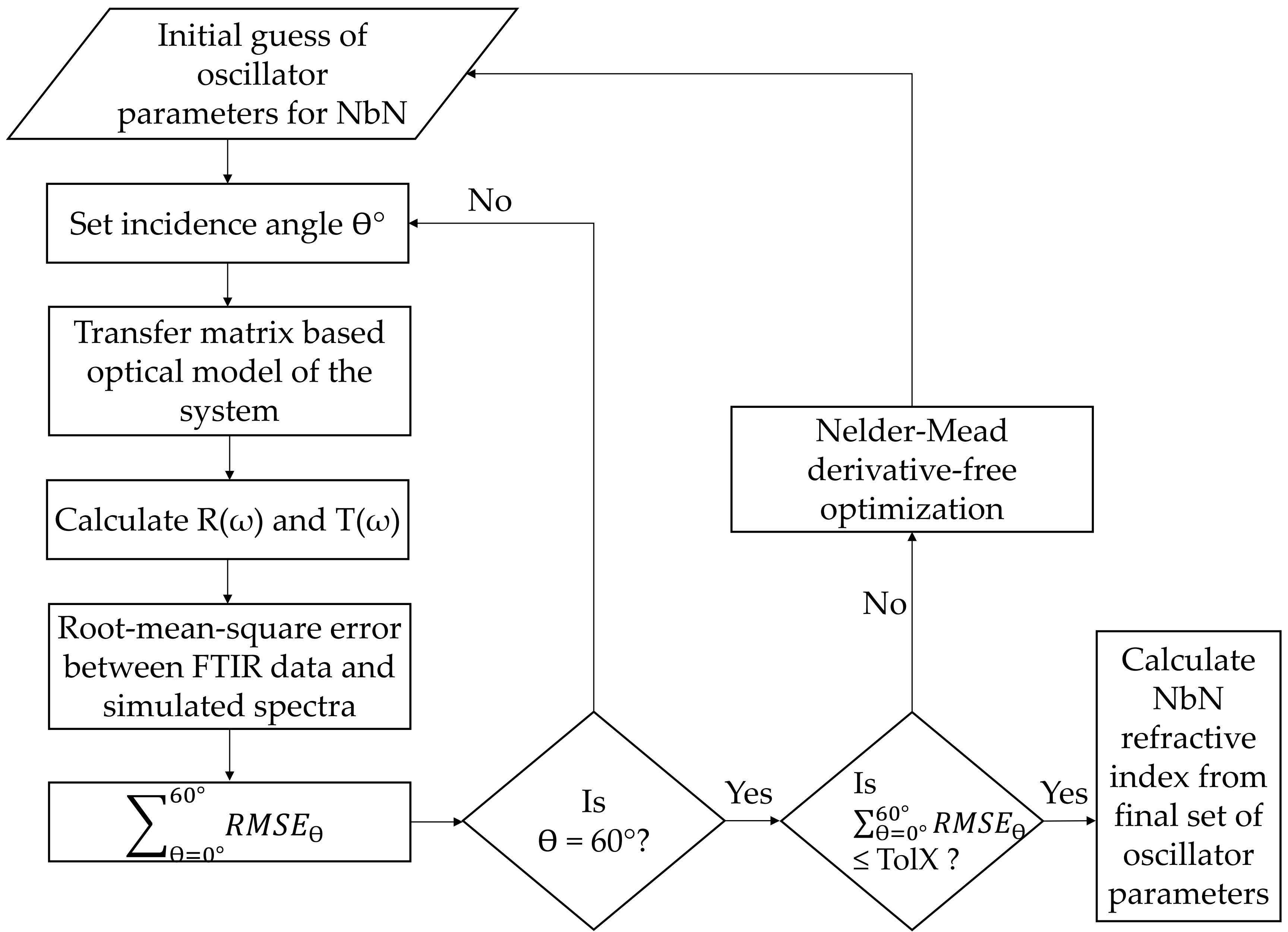


(a) Normal incidence FTIR transmittance measurement. (b) Variable incidence angle FTIR reflectance measurement. Incidence angle, Θ is varied from 12° to 60°. IR source spectra is shown in inset.

Refractive index extraction

- Complex refractive index of CaF_2 was measured initially from the FTIR spectra of uncoated CaF_2
- Dielectric constant of NbN is represented by Drude-Lorentz oscillator model $\epsilon(\omega) = \epsilon_\infty + \sum_{k=1}^{N} s_k / \left(1 - (\omega/\omega_k)^2 - i\Gamma_k (\omega/\omega_k)\right)$
- Complex refractive index

$$\overline{n(\omega)} = n(\omega) + ik(\omega) = \sqrt{\epsilon(\omega)}$$


Initial guess of oscillator parameters for NbN

Set incidence angle Θ°

Transfer matrix based optical model of the system

Calculate R(ω) and T(ω)

Root-mean-square error between FTIR data and simulated spectra

$\sum_{\Theta=0°}^{60°} RMSE_\Theta$

Is Θ = 60°?

No

Yes

Is $\sum_{\Theta=0°}^{60°} RMSE_\Theta \leq$ TolX ?

No

Nelder-Mead derivative-free optimization

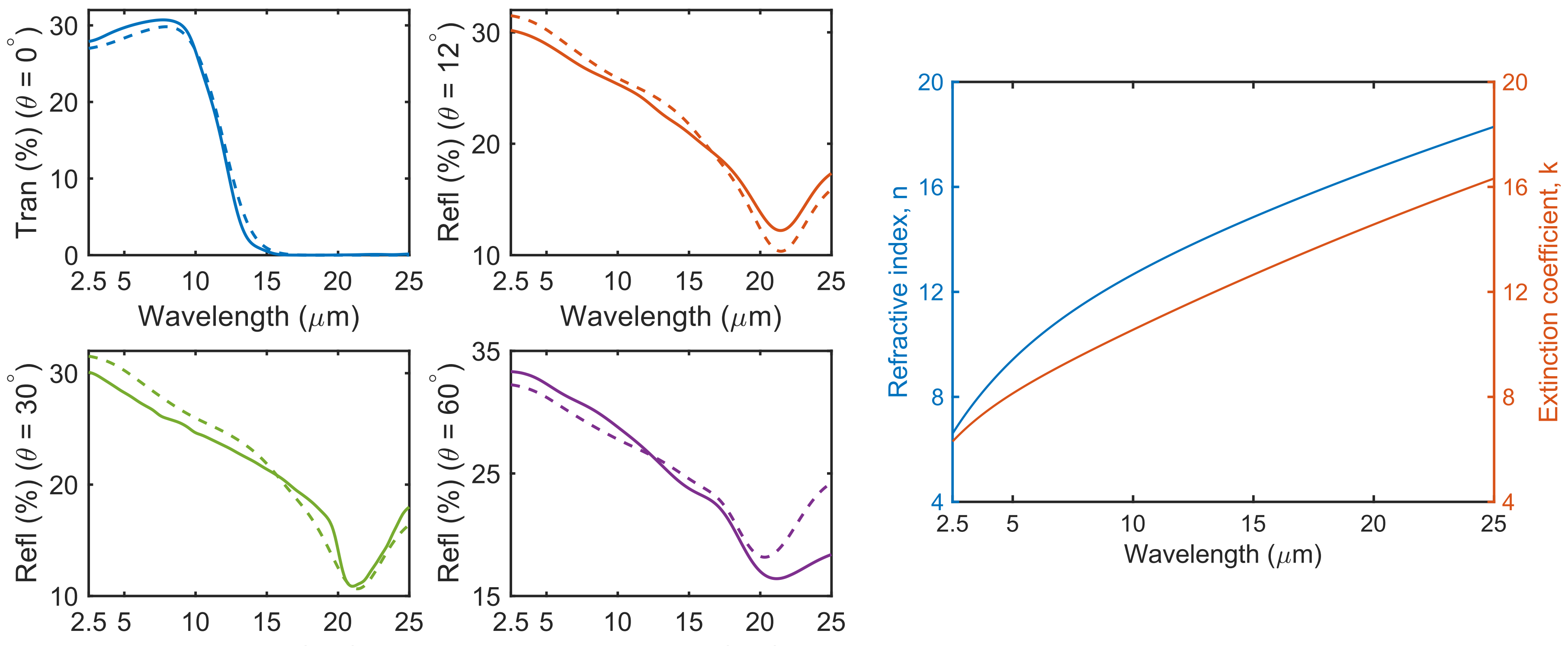
Yes

Calculate NbN refractive index from final set of oscillator parameters

TolX = error tolerance obtained empirically

Results and Discussion

- Calculated optical constant of CaF_2 was in good agreement with literature
- Subsequently refractive indices of NbN were determined for 2.5 to 25 μm
- The calculated optical constants of NbN should not be affected by the substrate; however, it has to be verified with silicon substrate



FTIR transmittance and reflectance spectra of NbN thin-film on CaF2 (solid line) and corresponding simulated spectra (dashed line), Calculated refractive indices of 10 nm thick NbN

New experiments with extracted data

- Extending SNSPDs sensitivity to the infrared wavelength using nano-antennas

Applications:

- High detection efficiency mid-infrared single-photon sensor
- Dark matter search

Acknowledgment

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References

1. V. Verma et al., APL Photonics, vol. 6, no. 5, p. 056101, 2021, 2. A. Banerjee et al., Optical Materials Express, vol. 8, no. 8, pp. 2072–2088, 2018, 3. A. E. Dane et al., Applied Physics Letters, vol. 111, no. 12, p. 122601, 2017, 4. W. Kaiser et al., Physical Review, vol. 127, no. 6, p. 1950, 1962.

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