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Modelling of Evanescent Field Scattering †

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Abstract: Evanescent field particle scattering is a promising method for single particle detection. In this study, we performed a detailed numerical analysis to show the possibilities and limitations of analytical models for predicting the capabilities of this sensing mechanism.

Keywords: particle sensor; evanescent field scattering; waveguide; Finite element modeling (FEM); Mie theory

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1. Introduction

The measurement of particulate matter has attracted much interest in recent years. In our ongoing work, we study the possibility of detecting nanoparticles using evanescent field scattering by particles on the surface of optical waveguides (WGs) [1,2]. A challenge in this context is the analytical modeling of the sensor response in order to deduce simple relations between particle size and transmission losses in the WG. Recently, it has been shown that the well-known solutions of traditional plane-wave Mie scattering can be directly transformed to the situation of evanescent field scattering using complex angle rotation [3]. However, the underlying model ignores the influence of the interface and does not consider guided modes. It is not at all established if, and how reliably, this model can be extrapolated towards single mode WGs. In this work, we use extensive finite element method (FEM) simulations to analyze, in much detail, scattering by a particle on a WG and scattering by a particle on an interface where a plane wave undergoes total internal reflection (TIR). Furthermore, we compare these results to analytical solutions of evanescent field scattering.

2. Results and Discussion

The analytical calculations were performed based on the formalism outlined in [3]. For simplicity, we limited our study to a 2D model and s-polarized light at a single wavelength of 650 nm (in analogy to ongoing experiments [1]). Finite element method (FEM) simulations were performed using COMSOL®. A WG height of 150 nm, Si_3N_4 as the WG material, and a refractive index of 2.0 for the particle were assumed. For the TIR simulation at the interface, the angle of incidence of the plane wave was chosen to correspond to the mode angle of the WG mode.

Figure 1 shows the simulation results for scattering by a spherical particle of a plane wave in air, at an interface, and on top of a waveguide. Evanescent field scattering significantly differs from classic Mie-scattering. Comparing the scattering of a WG mode to the single interface TIR scattering, the scattered fields look very similar. However, there is one major difference because part of the scattered light can be coupled back into the WG. More detailed analysis shows that FEM simulations and the analytical results are indeed similar in the near field, where the main effects are related to the excited modes within the particle. In the far-field pattern, additional fine structures show up, which are not seen in the analytical model and which we attribute to influences from the interface (Figure 1b). This must not be ignored, if one is interested in the detailed scattering distribution.

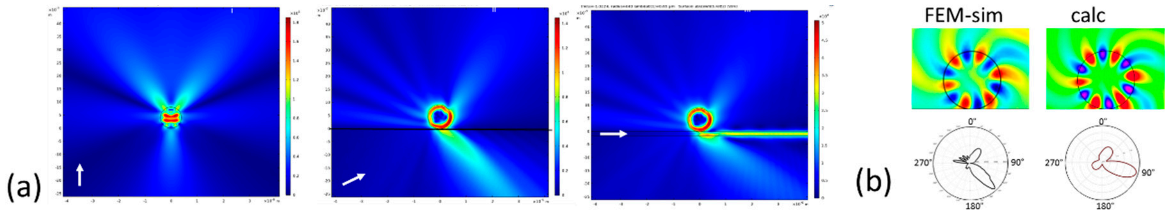

Figure 1. Scattering from a particle with r = 440 nm. (**a**) The absolute value of the scattered electric field is plotted for three different scattering scenarios: (i) particle exposed to a plane wave in air, (ii) particle exposed to the evanescent field of a plane wave, which undergoes total internal reflection at an interface, and (iii) particle exposed to the evanescent field of a guided mode in a waveguide. Arrows indicate the direction of the incoming wave. (**b**) Comparison of simulation with analytical calculation for near-field (upper row) and far-field (lower row): for the near field the real value of the scattered electric field is plotted and polar plots display the angular dependence of the electric field amplitude in the far field.

Comparing the particle size dependence of the transmission through the waveguide with the total scattered intensity retrieved in the FEM models as well as in the analytical model, we see a clear quantitative correspondence (Figure 2). WG and TIR scattering simulations provide almost identical solutions to the analytical model. On the other hand, even though peaks appear at the same positions, the results from classical Mie scattering of a plane wave are significantly different and completely fail to describe the evanescent field scattering signal.

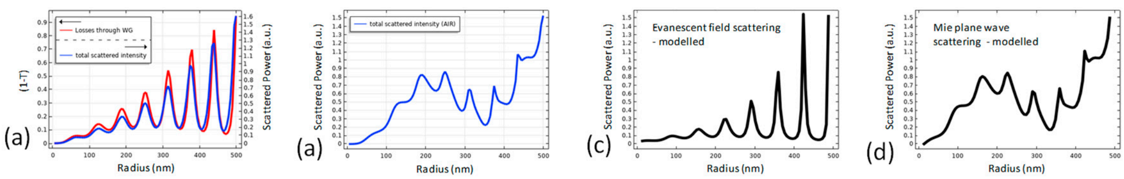

Figure 2. Simulated (**a**,**b**) and modelled (**c**,**d**) signals as a function of particle radius: (**a**) Total scattered intensity from TIR evanescent field scattering simulation compared to the losses of transmission through the waveguide. (**b**) Simulated MIE scattering of a plane wave. (**c**) Total scattered intensity from the analytical model of evanescent field scattering. (**d**) Modelled Mie scattering of a plane wave.

In conclusion, the overall size dependent signal from evanescent field scattering can be well modelled using simple models with analytical solutions. On the other hand, the simple analytical models fail to adequately describe details of the scattering function, since they do not include effects from the surface. Extension of the FEM models towards full 3D simulations is ongoing in order to generalize our conclusions.

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Conflicts of Interest: The authors declare no conflict of interest.

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