Nonlocal hydrodynamic Drude model of nano-plasmonic optical devices

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Summary. As optical devices get much smaller than the wavelength of the operating light, local material models for metallic structures like the Drude model and the Lorentz model become inadequate to describe accurately the light-matter interactions. To overcome this, a sophisticated non-local hydrodynamic Drude model has been proposed. We discuss a weak formulation of the nonlocal hydrodynamic Drude model in the frequency domain and apply the finite element method for scattering and propagating mode problems to demonstrate the dramatic impact of non-local effects on the device characteristics.

1 Introduction

The dispersive material properties of plasmonic structures are usually described by the Drude model and the Lorentz model. These material models take into account spatially purely local interactions between electrons and the light. Recent investigations have shown that these local models are inadequate as the size of the plasmonic structure becomes much smaller than the wavelength of the exciting light \[1, 2\]. To overcome this, a sophisticated nonlocal material model is required, such as the hydrodynamic model of the electron gas \[3\].

The hydrodynamic model is formulated by coupling macroscopic Maxwell’s equations with the equations of motion of the electron gas. This gives rise to a hydrodynamic polarization current. Considering only the kinetic energy of the free electrons, it yields the hydrodynamic current. This gives rise to a non-zero hydrodynamic current depend harmonically on \(z\). The frequency-domain solution based on Mie theory is available. The analytical Mie results. Appropriate Sobolev spaces for the electric field \(E\) and the hydrodynamic current \(J_{HD}\) are \(H(\text{curl}, \Omega)\) and \(\text{curl} E\), respectively. This restricts the hydrodynamic current to the metallic domain, and imposes a zero normal component on the boundary of the metal.

One can use textbook Nédelec finite element spaces to discretize \(H(\text{curl}, \Omega)\) and \(\text{curl} E\), leading to a consistent discretization of the problem, fulfilling the required boundary and material interface conditions \[6, \textit{Ch. 5}\]. Special geometries such as \(z\)-invariant structures or with a rotational symmetry, can be treated as in the standard Maxwell case. This allows for the computation of plasmon-polariton waveguide modes of a \(z\)-invariant structure on a 2D cross-section domain. In this case it is assumed that the electric field and the hydrodynamic current depend harmonically on \(z\): \(E(x, y, z) = E(x, y)e^{ikz}\), \(J_{HD}(x, y, z) = J_{HD}(x, y)e^{ikz}\) Replacing all \(z\)–derivatives in the coupled system \((1), (2)\) with \(ik\) yields a quadratic eigenvalue problem for the propagation constant \(k_z\).

2 Weak formulation

Appropriate Sobolev spaces for the electric field \(E\) and the hydrodynamic current \(J_{HD}\) are \(H(\text{curl}, \Omega)\) and \(H(\text{div}, \Omega_m)\), leading to a consistent discretization of the problem, fulfilling the required boundary and material interface conditions \[6, \textit{Ch. 5}\]. Special geometries such as \(z\)-invariant structures or with a rotational symmetry, can be treated as in the standard Maxwell case. This allows for the computation of plasmon-polariton waveguide modes of a \(z\)-invariant structure on a 2D cross-section domain. In this case it is assumed that the electric field and the hydrodynamic current depend harmonically on \(z\): \(E(x, y, z) = E(x, y)e^{ikz}\), \(J_{HD}(x, y, z) = J_{HD}(x, y)e^{ikz}\) Replacing all \(z\)–derivatives in the coupled system \((1), (2)\) with \(ik\) yields a quadratic eigenvalue problem for the propagation constant \(k_z\).

3 Numerical examples

3.1 Cylindrical plasmonic nanowires

We validate the present approach by simulating a test case of cylindrical nanowire as in \[1\], for which an analytical solution based on Mie theory is available. Consistent with the observations in \[1\], peaks due to nonlocal interactions are present only beyond the bulk plasma frequency, c.f. Fig. \[1\]. The positions of the surface plasmon resonance and the nonlocal hydrodynamic Drude resonances agree very good with the analytical Mie results.
3.2 V groove channel plasmon-polariton resonances

To demonstrate capability of the method to handle an arbitrary shaped geometry, we simulate a channel plasmon-polariton (CPP) waveguide with a V groove.

We consider a V groove configuration as shown in clip of Fig. 2. First we simulated it for the local Drude model. As seen from the dashed curve in Fig. 2, several resonance modes are excited. When this setting is simulated with the nonlocal Drude model, the mode spectrum changes significantly (solid-line curve). Some of the local Drude mode modes such as at \( \omega / \omega_p = 0.466485 \) and \( \omega / \omega_p = 0.605087 \) undergo noticeable shifts towards high frequency. As in the case of the cylindrical nanowires, also for the V groove waveguide a completely new set of resonances appear at the frequencies beyond the plasma frequency. For the present simulation setting, some of these hydrodynamic resonance modes are more prominent than the higher order waveguide resonance modes. It gives the indication that the modal properties of the CPP waveguides change significantly with the inclusion of nonlocal effects.

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References