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HAL Id: hal-01974072
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Submitted on 8 Jan 2019

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High order curvilinear DGTD method for local and nonlocal plasmonics
Advanced computational methods for nano-optical applications (1A4)

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Progress In Electromagnetics Research Symposium - PIERS 2018
Toyama, Japan, August 1-4, 2018
Context and objective of the study

Spatial dispersion effects in metals

- Various models exist for modeling metal dispersion for the study of plasmon waves.
- The most famous is the Drude model describing permittivity function of noble metals.
- Such models share a common assumption: the local response assumption (LRA).
- LRA states that, at any point of the metal, the polarization of the electrons only depends on the electromagnetic fields at this precise point.
- For scales approaching the nanometer, plasmons exhibit features that cannot be correctly predicted in the LRA framework.
- Modified models are required, called non-local models (NLM), owing to their accounting for what happens in the vicinity of the electron to determine its response.
- Quantum HydroDynamic (QHD) is one popular (semiclassical) theory.

Numerical modeling of QHD

- Frequency-domain and time-domain settings.
- Mostly considered in 2D with finite element (FE) and finite difference (TD) methods.
- Resource demanding (CPU and memory) in 3D.
Context and objective of the study

Numerical modeling of QHD: some related works

- **Time-domain setting (FDTD)**
  J.M. McMahon, S.K. Gray and G.C. Schatz
  Phys. Rev. B 82, 035423, 2010
  And many other references ...

- **Time-domain setting (DGTD)**
  A. Hille, M. Moeferd, C. Wolff, C. Matyssek, R. Rodriguez-Oliveros, C. Prohm
  J. Niegemann, S. Grafström, L.M. Eng and K. Busch
  Y. Grynko, T. Zentgraf, T. Meier and J. Förstner

- **Frequency-domain setting (FEM)**
  K.R. Hiremath, L. schiedrich and F. Schmidt
  N.A. Mortensen, S. Raza, M. Wubs, T. Sndergaard and S.I. Bozhevolnyi
  Nature Comm., Vol. 5, 2014

- **Frequency-domain setting (HDG - Hybridized DG)**
  L. Li, S. Lanteri, N.A. Mortensen and M. Wubs
Context and objective of the study

**Context:** development of high order finite element type solvers for time-domain plasmonics

**Objective:** impact of high order treatment of curvilinear geometries on accuracy and performance of a DGTD method for studying nonlocal dispersion effects

**Modeling setting:** linearized nonlocal hydrodynamic Drude model

A. Moreau, C. Ciraci and D.R. Smith
Physical Review B 87, 045401, 2013

S. Raza, S.I. Bozhevolnyi, M. Wubs, N.A. Mortensen

Left figure: molecule sensing with nanocubes.
Right figure: nanocube setup to study the influence of nonlocal dispersion on gap plasmons (ongoing work in collaboration with A. Moreau, Institut Pascal, France).
1. Numerical framework: the DG method

2. Quantum HydroDynamic (QHD) modeling of spatial dispersion

3. Curvilinear DGTD method for the Maxwell-QHD equations

4. Numerical results

5. Software

6. Closure
1 Numerical framework: the DG method

2 Quantum HydroDynamic (QHD) modeling of spatial dispersion

3 Curvilinear DGTD method for the Maxwell-QHD equations

4 Numerical results

5 Software

6 Closure
Numerical framework: the DG method

Context

- Somewhere between a finite element and a finite volume method, gathering many good features of both
- Extensively developed by the CFD community
- Application to wave propagation problems naturally followed

(a) Finite elements: continuous, non-constant-per-cell solution
(b) Finite volumes: discontinuous, constant-per-cell solution
(c) Discontinuous Galerkin: discontinuous, non-constant-per-cell solution
Numerical framework: the DG method

Classical DG formulation
- Naturally adapted to heterogeneous media and discontinuous solutions
- Can easily deal with unstructured, possibly non-conforming meshes ($h$-adaptivity)
- High order with compact stencils and non-conforming approximations ($p$-adaptivity)
- Usually rely on polynomial interpolation but can also accommodate alternative basis expansions
- But leads to larger problems compared to continuous finite element methods

DGTD: Discontinuous Galerkin Time-Domain method
- Increasingly studied since 2000
  - L. Fezoui, S. Lanteri, S. Lohrengel and S. Piperno, ESAIM: M2AN, Vol. 39, No. 6, 2005
- For nanophotonics
DG for electromagnetic wave propagation in heterogeneous media

- Heterogeneity is ideally treated at the element level
  - Discontinuities occur at material (i.e. element) interfaces
  - Mesh generation process is simplified
- Wavelength varies with $\varepsilon$ and $\mu$
  - For a given mesh density, approximation order can be adapted at the element level in order to fit to the local wavelength

Discretization of irregularly shaped domains

- Unstructured simplicial meshes
- The basic support of the DG method is the element (triangle in 2D and tetrahedron in 3D)
- Local refinement is facilitated by allowing non-conformity
- Non-conformity opens the route to the coupling of different discretization methods (e.g. structured/unstructured)
- For time-domain problems, mass matrix is block diagonal (worst case) or diagonal
  
Outline

1. Numerical framework: the DG method

2. Quantum HydroDynamic (QHD) modeling of spatial dispersion

3. Curvilinear DGTD method for the Maxwell-QHD equations

4. Numerical results

5. Software

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Quantum HydroDynamic (QHD) modeling of spatial dispersion

Constitutive equations for metals

- Electric polarization: \( \mathbf{P} = \mathbf{P}_b + \mathbf{P}_f \)
  - \( \mathbf{P}_b \) is the background polarization of the bound electrons
  - \( \mathbf{P}_f \) models the currents in the free electron gas

- Generalized dispersion model for bound electrons
  \[ \varepsilon_b(\omega) = \varepsilon_{\infty} - \frac{\sigma}{i\omega} - \sum_{l \in L_1} \frac{a_l}{i\omega - b_l} - \sum_{l \in L_2} \frac{c_l - i\omega d_l}{\omega^2 - e_l + i\omega f_l} \]

- QHD electron response: free gas modeled by a nonlinear fluid equation
  \[ m_{\text{elec}} \left( \partial_t + \mathbf{v} \cdot \nabla \right) \mathbf{v} = -q_{\text{elec}} \left( \mathbf{E} + \mathbf{v} \times \mathbf{B} \right) - m_{\text{elec}} \gamma \mathbf{v} - \nabla \left( \frac{\delta G[n]}{\delta n} \right) \]
  \[ \partial_t n + \nabla \cdot (n \mathbf{v}) = 0 \] (continuity equation)

where \( \frac{\delta G[n]}{\delta n} \) is the quantum pressure

- Selection of quantum mechanical effects through the energy functional \( G[n] \)
  \[ G[n] \approx G_\eta[n] = T^{\text{TF}}[n] + \frac{1}{\eta} T^{W}[n] + W_{\text{XC}} \]

Terms: kinetic (T), exchange correlation and potential energy (XC)
Quantum HydroDynamic (QHD) modeling of spatial dispersion

### Linearized QHD model

- Pure Thomas-Fermi theory
- First order linearized term of the quantum pressure: \( \beta^2 \frac{1}{n_0} \nabla n \)
- Three-dimensional Fermi gas: \( \beta = \sqrt{\frac{3}{5}} v_F \) where \( v_F \) is the Fermi velocity
- No von Weizäcker contribution as well as exchange correlation
- Linearizing around an equilibrium state, i.e. \( u(x, t) \approx u_0 + u_1(x, t) \) for \( u \in \{ n, v, E, B \} \), keeping the linear terms only and omitting the index \( (\cdot)_1 \)

\[
\begin{align*}
    m_{\text{elec}} \partial_t v &= -q_{\text{elec}} E - m_{\text{elec}} \gamma v + m_{\text{elec}} \beta^2 \frac{1}{n_0} \nabla n \quad (1) \\
    \partial_t n &= -n_0 \nabla \cdot v \quad (2)
\end{align*}
\]

assuming \( \partial_t n_0 = v_0 = E_0 = B_0 = 0 \).

- Using \( J_{\text{free}} = n_0 q_{\text{elec}} v \), the current density of free electrons in the fluid, and (2) in \( \partial_t (1) \)

\[
\partial_{tt} J_{\text{free}} + \gamma \partial_t J_{\text{free}} - \beta^2 \nabla (\nabla \cdot J_{\text{free}}) - \omega_P^2 \varepsilon_0 \partial_t E = 0 \quad \text{with} \quad \omega_P = \sqrt{\frac{n_0 b q_{\text{elec}}^2}{\varepsilon_0 m_{\text{elec}}}}
\]

- First order form

\[
\begin{align*}
    \partial_t J_{\text{free}} + \gamma J_{\text{free}} - \beta^2 \nabla Q - \omega_P^2 \varepsilon_0 E &= 0 \\
    \partial_t Q - \nabla \cdot J_{\text{free}} &= 0
\end{align*}
\]
Quantum HydroDynamic (QHD) modeling of spatial dispersion

**Time-domain Maxwell-QHD equations**

\[
\begin{align*}
\nabla \times \mathbf{E} + \mu_0 \partial_t \mathbf{H} & = 0 \\
\nabla \times \mathbf{H} - \varepsilon_0 \varepsilon_\infty \partial_t \mathbf{E} - \mathbf{J}_{\text{free}} - \mathbf{J}_{\text{bound}} & = 0 \\
\partial_t \mathbf{J}_{\text{free}} + \gamma \mathbf{J}_{\text{free}} - \beta^2 \nabla Q - \omega_P^2 \varepsilon_0 \mathbf{E} & = 0 \\
\partial_t Q - \nabla \cdot \mathbf{J}_{\text{free}} & = 0 \\
-J_{\text{bound}} + \mathbf{J}_0 + \sum_{l \in L_1} \mathbf{J}_l + \sum_{l \in L_2} \mathbf{J}_l & = 0 \\
-J_0 + \left( \sigma + \sum_{l \in L_2} d_l \right) \mathbf{E} & = 0 \\
-J_l + a_l \mathbf{E} - b_l \mathbf{P}_l & = 0 \quad \forall l \in L_1 \\
-\partial_t \mathbf{P}_l + \mathbf{J}_l & = 0 \quad \forall l \in L_1 \\
-\partial_t \mathbf{J}_l + (c_l - d_l f_l) \mathbf{E} - f_l \mathbf{J}_l - e_l \mathbf{P}_l & = 0 \quad \forall l \in L_2 \\
-\partial_t \mathbf{P}_l + d_l \mathbf{E} + \mathbf{J}_l & = 0 \quad \forall l \in L_2
\end{align*}
\]

with \(\{\varepsilon_\infty, \sigma, a_l, b_l, c_l, d_l, e_l, f_l\} \in \mathbb{R}\) and \(L_{1,2}\) being the number of first and second order poles, respectively, in the GDM for local dispersion.
Outline

1 Numerical framework: the DG method

2 Quantum HydroDynamic (QHD) modeling of spatial dispersion

3 Curvilinear DGTD method for the Maxwell-QHD equations

4 Numerical results

5 Software

6 Closure
Main principles of a DG method

1. Definition of the computational domain
   - Unstructured mesh with tetrahedral elements
   - Structured or unstructured mesh with hexahedral elements
   - Local refinement (possibly non-conforming)

2. Discretization in space
   - Element-wise weak formulation
   - Numerical traces (fluxes) at inter-element boundaries to recover consistency
     ⇒ Solution of a Riemann problem
   - Numerical integration of elementary terms on a reference element

3. Time integration of the semi-discrete equations
   - Explicit scheme (in most of the cases)
   - Implicit scheme or locally implicit scheme
   - Local time stepping
Riemann problem. Figure (d) illustrates a field discontinuity at the interface of two mesh cells. Generally, this is subject to a generalized Riemann problem as shown in (e). Considering only the leading term within the vicinity of the interface (orange region), simplifies the generalized Riemann problem to a standard Riemann problem with a piecewise constant solution (f). Its solution in the \((x - t)\) space is shown in (g).
Main principles of a DG method

- $Z$: impedance - $Y$: admittance - $\alpha$: upwinding parameter

\[
\{A\}_{--} := A^- + A^+, \quad [A]_{--} := A^- - A^+,
\]

- Numerical flux for the Maxwell part

\[
\begin{align*}
\mathbf{n} \times \mathbf{H}^- &= \frac{1}{Z^- + Z^+} \left( \mathbf{n} \times \{Z \mathbf{H}\}_{--} - \alpha \mathbf{n} \times (\mathbf{n} \times [\mathbf{E}]_{--}) \right), \\
\mathbf{n} \times \mathbf{E}^- &= \frac{1}{Y^- + Y^+} \left( \mathbf{n} \times \{Y \mathbf{E}\}_{--} + \alpha \mathbf{n} \times (\mathbf{n} \times [\mathbf{H}]_{--}) \right)
\end{align*}
\]

- Numerical flux for the hydrodynamic Drude model part

\[
\begin{align*}
(\beta^-)^2 \mathbf{Q}^- &= \frac{\beta^- \beta^+}{\beta^- + \beta^+} \left( \{\beta \mathbf{Q}\}_{--} - \alpha (\mathbf{n} \cdot [\mathbf{J}]_{--}) \right), \\
(\beta^-)^2 \mathbf{n} \cdot \mathbf{J}^- &= \frac{(\beta^-)^3 (\beta^+)^3}{(\beta^-)^3 + (\beta^+)^3} \left( \mathbf{n} \cdot \{\frac{\mathbf{J}}{\beta}\}_{--} - \alpha [\mathbf{Q}]_{--} \right)
\end{align*}
\]

with on the boundary of the nonlocal dispersive domain

\[
\mathbf{Q}^- |_{\partial \Omega_{NL}} = Q^- \quad \text{and} \quad \mathbf{n} \cdot \mathbf{J}^- |_{\partial \Omega_{NL}} = 0
\]
Curvilinear DGTD method for the Maxwell-QHD equations

Dealing with *geometry approximation* error

- NURBS-enhanced finite element method (NEFEM)
  High order DGTD method for computing resonant frequencies and modes

- Isogeometric analysis
  Directly employs the geometric basis functions as approximation space
  A. Buffa, G. Sangallia and R. Vázquez

- Our setting: isoparametric FEM

Second order mapping from the reference element $\hat{\tau}$ to the physical element $\tau_i$
Validation: standing wave in a spherical PEC cavity

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>2.01</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>2.14</td>
</tr>
<tr>
<td>$P_2$</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>2.19</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>2.20</td>
</tr>
<tr>
<td>$P_3$</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>2.19</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>2.20</td>
</tr>
<tr>
<td>$P_4$</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>2.18</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>2.18</td>
</tr>
</tbody>
</table>

Convergence rates of the spherical cavity case for different approximation orders and fluxes, with linear and curvilinear meshes of increasing refinement ($\alpha$ is the upwinding parameter).
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Numerical results
Scattering by a gold nanosphere

Four different discretization for a scattered sphere in vacuum. Figures (a) and (b) have the same number of elements and differ by the geometric representation order from linear to quadratic. Figure (c) is a refined version of (a) and (d) is the high order version.
Numerical results
Scattering by a gold nanosphere

Extinction cross-section spectra on meshes M1 and M2.
Comparison of the extinction cross-section spectra of a metallic nano-sphere in dependence of the polynomial interpolation order and the geometric mesh order, i.e. linear or quadratic mesh elements.
Numerical results

Scattering by a gold nanosphere

Relative error is given with respect to the analytical nonlocal Mie solution

<table>
<thead>
<tr>
<th></th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 – Linear</td>
<td>33.33%</td>
<td>29.95%</td>
<td>28.83%</td>
<td>28.80%</td>
</tr>
<tr>
<td>M1 – Quadratic</td>
<td>43.67%</td>
<td>18.51%</td>
<td>6.60%</td>
<td>2.38%</td>
</tr>
<tr>
<td>M2 – Linear</td>
<td>33.50%</td>
<td>11.07%</td>
<td>7.18%</td>
<td>5.34%</td>
</tr>
<tr>
<td>M2 – Quadratic</td>
<td>39.40%</td>
<td>10.07%</td>
<td>3.58%</td>
<td>0.96%</td>
</tr>
</tbody>
</table>
Extinction cross-section spectra on meshes M1 and M2.
Comparison of the extinction cross-section spectra of a metallic nanosphere in dependence of the polynomial interpolation order and the geometric mesh order, i.e. linear or quadratic mesh elements.
### Numerical results

Scattering by a gold nanosphere

<table>
<thead>
<tr>
<th></th>
<th>M1 – Quadratic – $P_3$</th>
<th>M2 – Linear – $P_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L^2$–error (Mie)</td>
<td>6.6%</td>
<td>5.34%</td>
</tr>
<tr>
<td># Cells</td>
<td>13827</td>
<td>14334</td>
</tr>
<tr>
<td># Sphere cells</td>
<td>46</td>
<td>292</td>
</tr>
<tr>
<td># High order cells</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td># Iterations</td>
<td>7060</td>
<td>90933</td>
</tr>
<tr>
<td>Memory</td>
<td>1481 MB</td>
<td>1980 MB</td>
</tr>
<tr>
<td>Time for 100 iterations (seq.)</td>
<td>374 s</td>
<td>703 s</td>
</tr>
<tr>
<td>Total time in loop (seq.)</td>
<td>26404 s</td>
<td>639259 s</td>
</tr>
<tr>
<td>Speedup</td>
<td>24.2</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#proc</th>
<th>$T$ [s]</th>
<th>Speedup</th>
<th>#proc</th>
<th>$T$ [s]</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>186</td>
<td>2.0</td>
<td>2</td>
<td>380</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>94</td>
<td>4.0</td>
<td>4</td>
<td>200</td>
<td>3.5</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>7.5</td>
<td>8</td>
<td>105</td>
<td>6.7</td>
</tr>
<tr>
<td>12</td>
<td>37</td>
<td>10.1</td>
<td>12</td>
<td>73</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Mesh characteristics and performance figures for DGTD simulations with mesh M1 based on curvilinear elements and a polynomial order $P_3$ versus refined mesh M2 based on linear elements and a polynomial order $P_4$. The listed values only contain the actual mesh and do not contain ghost cells due to boundary conditions and domain decomposition for the parallel MPI runs. Simulation have been performed on an Intel Xeon CPU E5-2630 v2 2.6 GHz machine with 64 GB RAM.
Numerical results
Nanosphere dimer

- Material: gold, $\omega_P = 1.39e + 16$ rad/s, $\gamma = 3.23e + 13$ rad/s and $\beta = 0.84$ m/s
- Sphere radius: 10 nm
- Gap size: 2 nm

Nanosphere dimer system. Left figure sketches the dimer setup with an $e_x$ polarized incident plane wave. Right figure shows the 3D field distribution of the electric field on the dimer surface and on a cutting plane and along the dimer axis.
Numerical results
Nanosphere dimer

Nanosphere dimer field plot at the third resonance (volume). Left figure: 3D field distribution of the electric field if a local dispersion model is employed. Right figure: a nonlocal dispersion model is used. Nonlocality smears out vacuum-metal interface and builds up a penetration layer. The discontinuities of the DGTD method are clearly visible.
Nanosphere dimer: local vs. nonlocal dispersion. Comparison of local and nonlocal extinction CS.
Nanosphere dimer: local vs. nonlocal dispersion. Left figure: 3D field distribution at third resonance of the electric field if a local dispersion model is employed. Right figure: a nonlocal dispersion model is used. Nonlocality widens the gap plasmon resonance due to stronger field enhancements.
Summary

- Centered DGTD solution almost is polluted by spurious modes
- Upwind DGTD introduces numerical dissipation and damps spurious modes
- The higher numerical dissipation of upwind DGTD can make the detection of weak resonances impossible
- Significant blue-shift for all resonances when switching to nonlocal dispersion
- Regarding the near-field distribution, nonlocality leads to a stronger penetration of the field
- Nonlocality leads to a field enhancement on the surface and widens the gap mode
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Software

Development of a dedicated software suite for nanophotonics

**DIOGENeS - DIscOntinuous GalErkin Nano Solvers**
https://diogenes.inria.fr

- 3D time-domain and frequency-domain Maxwell equations
- High order DG and HDG (Hybridized DG) methods
- Drude, Drude-Lorentz and generalized dispersion models
- Linearized hydrodynamic Drude model
- Unstructured and hybrid cubic/tetrahedral meshes
- Affine and curvilinear elements
- Optimized low storage Runge-Kutta time schemes
- PDE-based and algebraic domain decomposition solvers (frequency-domain)
- Hybrid MIMD/SIMD parallelization based on MPI/OpenMP
- CFS-PML, TF/SF formulation, etc.
Software

Positioning

- Not a commercial software but rather a tool to enable multi-disciplinary collaborations

- Main objectives
  - Enhance the capabilities of DG type methods for dealing with realistic scientific and technological applications
  - Contribute to solving concrete problems requiring advanced modeling and simulation, in addition to experimental design
  - Participate to collaborative projects with physicists facing difficulties with their own simulation tools

- Under development since December 2015
  First official release planned for end of 2018
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Summary

- Improved numerical treatment of curvilinear geometries
- Higher order accuracy thanks to higher order mappings
- Better resolution of plasmonic features
- Computational efficiency thanks to coarser meshes

Future works

- Generalized nonlocal optical response (GNOR) model
- Spill-out models
- Nonlinear hydrodynamic Drude model

Thank you for your attention!