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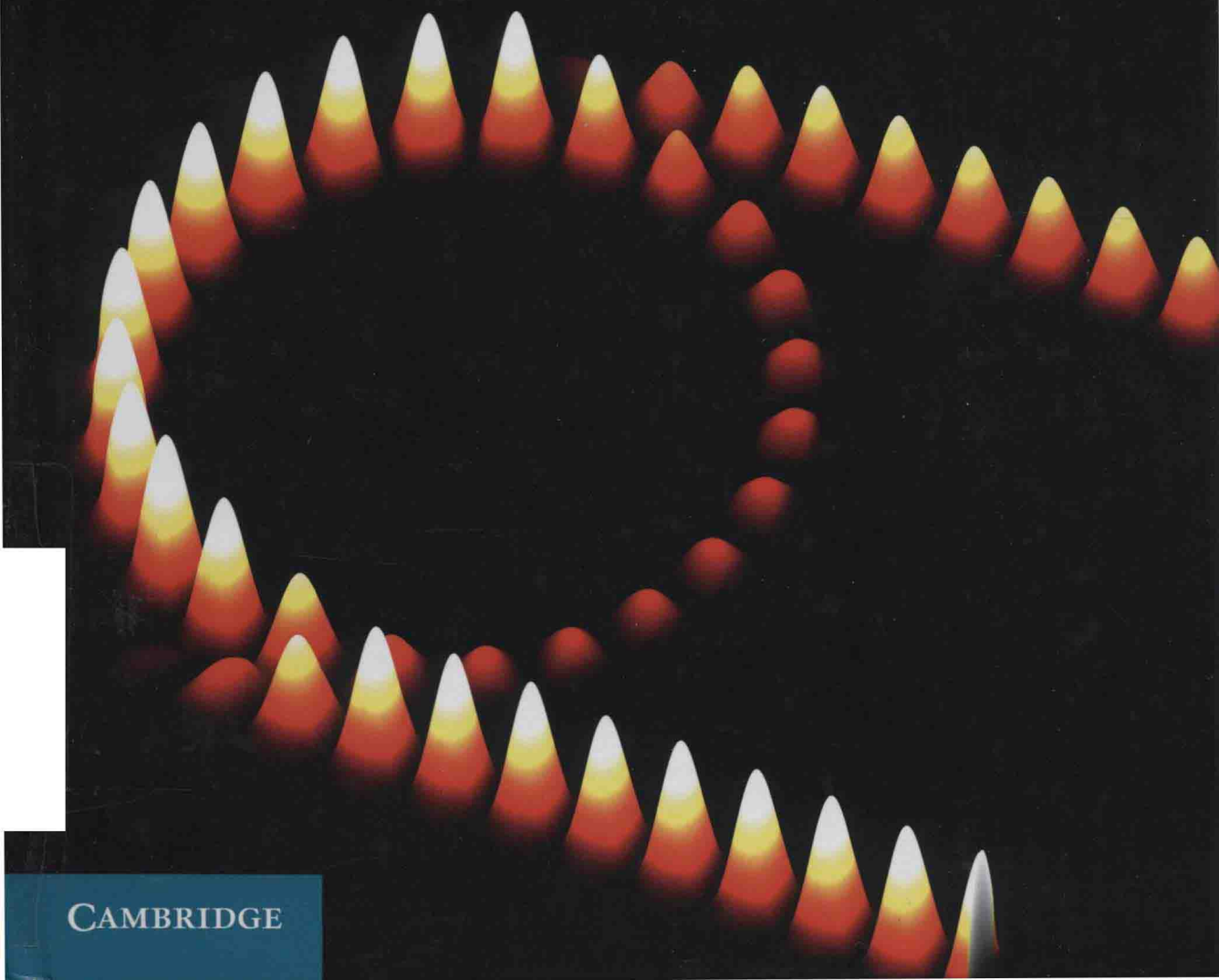
Plasmonic Nanoelectronics and Sensing

ER-PING LI and HONG-SON CHU



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ER-PING LI and HONG-SON CHU
A*STAR Institute of High Performance Computing, Singapore

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Plasmonic Nanoelectronics and Sensing

Plasmonic nanostructures provide new ways of manipulating the flow of light, with nanostructures and nanoparticles exhibiting optical properties never before seen in the macro-world. Covering plasmonic technology from fundamental theory to real-world applications, this work provides a comprehensive overview of the field.

- Discusses the fundamental theory of plasmonics, enabling a deeper understanding of plasmonic technology
- Details numerical methods for modeling, design, and optimization of plasmonic nanostructures
- Includes step-by-step design guidelines for active and passive plasmonic devices, demonstrating the implementation of real devices in the standard CMOS nanoscale electronic–photonic integrated circuit to help cut design, fabrication, and characterization time and cost
- Includes real-world case studies of plasmonic devices and sensors, explaining the benefits and downsides of different nanophotonic integrated circuits and sensing platforms.

Ideal for researchers, engineers, and graduate students in the fields of nanophotonics and nanoelectronics as well as optical biosensing.

Er-Ping Li is a Principal Scientist and Director of Nanophotonics and Electronics at the Institute of High Performance Computing, A*STAR, Singapore. He is a Fellow of the IEEE and of the Electromagnetics Academy, USA.

Hong-Son Chu is a Scientist at the Nanophotonics and Electronics Department of the Institute of High Performance Computing, A*STAR, Singapore. He is a member of the Optical Society of America, the IEEE, and the Materials Research Society.

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Contributors

1 Fundamentals of plasmonics and
2 Plasmonic properties of metal nanostructures
Yuriy A. Akimov
*A*STAR Institute of High Performance Computing, Singapore*

3 Frequency-domain methods for modeling plasmonics
Zhengtong Liu
*A*STAR Institute of High Performance Computing, Singapore*

4 Time-domain simulation for plasmonic devices
Iftikhar Ahmed and Eng Huat Khoo
*A*STAR Institute of High Performance Computing, Singapore*

6 Silicon-based active plasmonic devices for on-chip integration
Dim-Lee Kwong, Guo-Qiang Lo, and Shiyang Zhu
*A*STAR Institute of Microelectronics, Singapore*

7 Plasmonic biosensing devices and systems
Lin Wu and Ping Bai
*A*STAR Institute of High Performance Computing, Singapore*

Preface

Data communication and information processing are driving the rapid development of ultra-high speed and ultra-compactness in nano-photo-electronic integration. Plasmonics technology has in recent years demonstrated the promise to overcome the size mismatch between microscale photonic and nanoscale electronic integration, and it likely will be crucial for the next generation of on-chip optical nano-interconnects, enabling the deployment of small-footprint and low-energy integrated circuitry.

The phenomenon of surface plasmons was first observed in the Lycurgus cup, which is a Roman glass cage cup in the British Museum, London, UK. This special cup is made of a dichroic glass that shows a different color depending on the condition of illumination. Specifically, in daylight, the cup appears to have a green color, which means that light is being reflected from the cup; however, when a light is shone into the cup and transmitted through the glass, it appears to have a red color. Today, we know that this fascinating behavior is due to nanoscopic-scale gold and silver particles embedded in the glass. However, it took 1500 years and doubtless countless fantastic interpretations for a plausible explanation to emerge. In the last few decades, the phenomenon of surface plasmons has been extensively studied both theoretically and experimentally, and there have been attempts to use it for various applications ranging from solar-cell energy and sensing to nanophotonic devices.

This book presents the results from many years of our collective research in the fields of nanoplasmonics and its applications. It presents state-of-the-art plasmonics device modeling and design techniques, with novel developments in particular in CMOS-compatible integrated circuits and sensing technologies. We hope this book can serve as a good basis for further progress in this field, both in academic research and for industrial applications. The book consists of seven chapters, contributed by Yuriy Akimov, Zhengtong Liu, Iftikhar Ahmed, Eng Huat Khoo, Er-Ping Li, Hong-Son Chu, Wu Lin, and Bai Ping, from the Department of Electronics and Photonics, Institute of High Performance Computing, Singapore, and Shiyang Zhu, Patrick Guo-Qiang Lo, and Dim-Lee Kwong from the Institute of Microelectronics, Agency for Science Technology and Research, Singapore.

Chapter 1 introduces the fundamentals of plasmonics associated with Maxwell's theory and applications in plasmonics. Chapter 2 provides an introduction to the plasmonic properties of metal nanostructures. Chapter 3 presents the modeling and simulation of plasmonics associated with plasmonic devices by implementation of frequency-domain numerical methods. In Chapter 4, time-domain simulation methods, in

particular the finite-difference time-domain method, are introduced for passive and active plasmonic device design. Chapter 5 describes the development of various passive plasmonic waveguides, in particular CMOS-compatible devices for on-chip nanoelectronic integration, and Chapter 6 presents CMOS-compatible active plasmonic devices for on-chip nanoelectronic integration. Both theoretical studies and experimental results are presented in these two chapters. The recent development of plasmonics for biosensing applications is presented in Chapter 7.

We gratefully acknowledge the research support from the Agency for Science Technology and Research, Singapore. Also acknowledged are the contributors to the book, Drs. Yuriy Akmov, Zhengtong Liu, Iftikhar Ahmed, Eng Huat Khoo, Wu Lin, Bai Ping, Shiyang Zhu, and Patrick Guo-Qiang Lo and Professor Dim-Lee Kwong, who did the really hard work. We also wish to express our gratitude to Mia Balashova and Julie Lancashire from Cambridge University Press for their great assistance in keeping us on schedule. Finally, we are grateful to all the contributors' families, without whose continuing support and understanding this book would never have been published.

We hope that this book will serve as a valuable reference for engineers, researchers, and post-graduate students in the fields of nanophotonics and nanoelectronics as well as optical biosensing. Even though much has been accomplished in these fields, we predict that many more exciting challenges will arise in these areas.

Er-Ping LI and Hong-Son CHU

Contents

1 Fundamentals of plasmonics

In this chapter, we give a brief introduction to the classical electrodynamics of metals that constitutes the basis of modern plasmonics. We review the Maxwell equations for electromagnetic fields and consider the main optical properties of metals within the local-response approximation. In conclusion, we give a general classification of plasmons that appear in metal structures.

1.1 Electromagnetic field equations

1.1.1 Maxwell's equations in a medium

Most of the electromagnetic phenomena occurring in metals are well described within the classical electrodynamics based on the *macroscopic Maxwell equations*. These equations assume the use of the statistically averaged (over an ensemble of the equivalent systems) electric and magnetic fields. Practically, the averaging is performed in space over "physically small" volumes, which are much smaller than the wavelength, but much longer than the mean interatomic distance. Within this approach, we neglect all field fluctuations that occur at atomic scales and consider only the macroscopic response of the medium.

In the absence of external charges and currents, the macroscopic Maxwell equations for electromagnetic fields in a medium can be written as follows:[1]

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}, \quad \nabla \cdot \boldsymbol{E} = 4\pi\rho, \tag{1.1}$$

$$\nabla \times \boldsymbol{B} = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} + \frac{4\pi}{c}\boldsymbol{j}, \quad \nabla \cdot \boldsymbol{B} = 0, \tag{1.2}$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic induction, ρ is the induced internal charge density, $\boldsymbol{j}$ is the induced electric current density, and c is the speed of light in vacuum. The induced charges and currents comprise the medium's response to the electromagnetic field, as a result of its polarization and magnetization.

[1] Throughout this chapter, all quantities and equations are written in the Gaussian unit system for a more natural description of electromagnetic fields. For conversion to the SI unit system, we refer the reader to the textbook by Jackson [1].

In general, the induced charges and currents are given with the *polarization* $\boldsymbol{P}$ and *magnetization* $\boldsymbol{M}$ fields,

$$\rho = -\nabla \cdot \boldsymbol{P}, \tag{1.3}$$

$$\boldsymbol{j} = \frac{\partial \boldsymbol{P}}{\partial t} + c\,\nabla \times \boldsymbol{M}, \tag{1.4}$$

that allow us to rewrite the macroscopic Maxwell equations in a simpler form,

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}, \quad \nabla \cdot \boldsymbol{D} = 0, \tag{1.5}$$

$$\nabla \times \boldsymbol{H} = \frac{1}{c}\frac{\partial \boldsymbol{D}}{\partial t}, \quad \nabla \cdot \boldsymbol{B} = 0, \tag{1.6}$$

where $\boldsymbol{D}$ and $\boldsymbol{H}$ are the auxiliary fields called the electric displacement and magnetic field, which are introduced to account for the polarization and magnetization of the medium,

$$\boldsymbol{D} = \boldsymbol{E} + 4\pi \boldsymbol{P}, \tag{1.7}$$

$$\boldsymbol{H} = \boldsymbol{B} - 4\pi \boldsymbol{M}. \tag{1.8}$$

Thus, the Maxwell equations in a medium give us the relation between two pairs of electric $\{\boldsymbol{E}, \boldsymbol{D}\}$ and magnetic $\{\boldsymbol{B}, \boldsymbol{H}\}$ fields. In this sense, Eqs. (1.5) and (1.6) do not form a closed set of equations until we provide *material relations* for the medium's response to electric and magnetic fields. In general, these relations are given by field-dependent functions for polarization $\boldsymbol{P} = \boldsymbol{P}(\boldsymbol{E})$ and magnetization $\boldsymbol{M} = \boldsymbol{M}(\boldsymbol{B})$ vectors that eventually result in material relations for the auxiliary fields $\boldsymbol{D} = \boldsymbol{D}(\boldsymbol{E})$ and $\boldsymbol{H} = \boldsymbol{H}(\boldsymbol{B})$.

1.1.2 Material equations

Establishing the relations for $\boldsymbol{D}(\boldsymbol{E})$ and $\boldsymbol{H}(\boldsymbol{B})$ is the key issue, since it describes how the medium responds to electromagnetic fields. In general, these relations are nonlinear. However, for $\boldsymbol{E}$ and $\boldsymbol{B}$ fields that are not too high, the auxiliary fields $\boldsymbol{D}(\boldsymbol{E})$ and $\boldsymbol{H}(\boldsymbol{B})$ can be approximated with linear functions. This is the so-called *linear-electrodynamics* approach. In this approximation, the response of the medium at a given point $\boldsymbol{r}$ and moment t is assumed to be a linear function of electromagnetic fields at any point $\boldsymbol{r}'$ taken at all preceding moments $t' < t$ in accordance with the causality principle,

$$D_i(t, \boldsymbol{r}) = \int_{-\infty}^{t} \mathrm{d}t' \int \mathrm{d}\boldsymbol{r}'\, \varepsilon_{ij}(t, t', \boldsymbol{r}, \boldsymbol{r}') E_j(t', \boldsymbol{r}'), \tag{1.9}$$

$$B_i(t, \boldsymbol{r}) = \int_{-\infty}^{t} \mathrm{d}t' \int \mathrm{d}\boldsymbol{r}'\, \mu_{ij}(t, t', \boldsymbol{r}, \boldsymbol{r}') H_j(t', \boldsymbol{r}'). \tag{1.10}$$

Note that here we write the dependence $\boldsymbol{B}(\boldsymbol{H})$ instead of $\boldsymbol{H}(\boldsymbol{B})$. It is caused by the symmetry of Maxwell's equations observed with respect to the field pairs $\{\boldsymbol{E}, \boldsymbol{D}\}$ and

$\{\boldsymbol{H}, \boldsymbol{B}\}$. Following this symmetry, it is more natural to consider the dependence $\boldsymbol{B}(\boldsymbol{H})$, rather than $\boldsymbol{H}(\boldsymbol{B})$. For this reason, the field $\boldsymbol{H}$ is commonly called the magnetic field, by analogy with the electric field $\boldsymbol{E}$, although it is actually an auxiliary quantity.

The functions $\varepsilon_{ij}(t, t', \boldsymbol{r}, \boldsymbol{r}')$ and $\mu_{ij}(t, t', \boldsymbol{r}, \boldsymbol{r}')$ in Eqs. (1.9) and (1.10) characterize the efficiency of the material response transfer from one point of space and time to another. For a medium that is homogeneous in space and time, the functions ε_{ij} and μ_{ij} depend on the differences $t - t'$ and $\boldsymbol{r} - \boldsymbol{r}'$. In this case,

$$D_i(t, \boldsymbol{r}) = \int_{-\infty}^{t} \mathrm{d}t' \int \mathrm{d}\boldsymbol{r}'\, \varepsilon_{ij}(t - t', \boldsymbol{r} - \boldsymbol{r}') E_j(t', \boldsymbol{r}'), \tag{1.11}$$

$$B_i(t, \boldsymbol{r}) = \int_{-\infty}^{t} \mathrm{d}t' \int \mathrm{d}\boldsymbol{r}'\, \mu_{ij}(t - t', \boldsymbol{r} - \boldsymbol{r}') H_j(t', \boldsymbol{r}'). \tag{1.12}$$

By performing the Fourier transform,

$$G(t, \boldsymbol{r}) = \frac{1}{(2\pi)^2} \iint G(\omega, \boldsymbol{k}) \mathrm{e}^{\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t)}\, \mathrm{d}\omega\, \mathrm{d}\boldsymbol{k},$$

of D_i, E_j, B_i, and H_j in the $(t, \boldsymbol{r})$ space, we get the material relations for the fields in the frequency–wavevector space $(\omega, \boldsymbol{k})$,

$$D_i(\omega, \boldsymbol{k}) = \varepsilon_{ij}(\omega, \boldsymbol{k}) E_j(\omega, \boldsymbol{k}), \tag{1.13}$$

$$B_i(\omega, \boldsymbol{k}) = \mu_{ij}(\omega, \boldsymbol{k}) H_j(\omega, \boldsymbol{k}). \tag{1.14}$$

Here, $\varepsilon_{ij}(\omega, \boldsymbol{k})$ and $\mu_{ij}(\omega, \boldsymbol{k})$ are the tensors of complex permittivity and permeability given by

$$\varepsilon_{ij}(\omega, \boldsymbol{k}) = \int_0^{\infty} \mathrm{d}t_1 \int \mathrm{d}\boldsymbol{r}_1\, \varepsilon_{ij}(t_1, \boldsymbol{r}_1) \mathrm{e}^{-\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{r}_1 - \omega t_1)}, \tag{1.15}$$

$$\mu_{ij}(\omega, \boldsymbol{k}) = \int_0^{\infty} \mathrm{d}t_1 \int \mathrm{d}\boldsymbol{r}_1\, \mu_{ij}(t_1, \boldsymbol{r}_1) \mathrm{e}^{-\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{r}_1 - \omega t_1)}, \tag{1.16}$$

where $t_1 = t - t'$ and $\boldsymbol{r}_1 = \boldsymbol{r} - \boldsymbol{r}'$.

For an isotropic medium, the properties of which are identical in any direction, $\varepsilon_{ij}(\omega, \boldsymbol{k})$ and $\mu_{ij}(\omega, \boldsymbol{k})$ can be composed of the unit tensor δ_{ij} and the tensor $k_i k_j$, since they are the only two tensors of second rank formed from the vector $\boldsymbol{k}$. In this case, we have

$$\varepsilon_{ij}(\omega, \boldsymbol{k}) = \left(\delta_{ij} - \frac{k_i k_j}{k^2}\right) \varepsilon_{\mathrm{t}}(\omega, \boldsymbol{k}) + \frac{k_i k_j}{k^2} \varepsilon_{\mathrm{l}}(\omega, \boldsymbol{k}), \tag{1.17}$$

$$\mu_{ij}(\omega, \boldsymbol{k}) = \left(\delta_{ij} - \frac{k_i k_j}{k^2}\right) \mu_{\mathrm{t}}(\omega, \boldsymbol{k}) + \frac{k_i k_j}{k^2} \mu_{\mathrm{l}}(\omega, \boldsymbol{k}). \tag{1.18}$$

Thus, among the nine components of each tensor ε_{ij} and μ_{ij}, only two components are independent, namely $\varepsilon_{\mathrm{t}}(\omega, \boldsymbol{k})$ and $\varepsilon_{\mathrm{l}}(\omega, \boldsymbol{k})$ for ε_{ij}, and $\mu_{\mathrm{t}}(\omega, \boldsymbol{k})$ and $\mu_{\mathrm{l}}(\omega, \boldsymbol{k})$ for μ_{ij}. The

meaning of those components becomes clear if we write $\boldsymbol{D}$ and $\boldsymbol{B}$ in vector form,

$$\boldsymbol{D}(\omega, \boldsymbol{k}) = \varepsilon_{\mathrm{t}}(\omega, \boldsymbol{k})\frac{\boldsymbol{k} \times (\boldsymbol{E} \times \boldsymbol{k})}{k^2} + \varepsilon_{\mathrm{l}}(\omega, \boldsymbol{k})\frac{\boldsymbol{k}(\boldsymbol{E} \cdot \boldsymbol{k})}{k^2},$$

$$\boldsymbol{B}(\omega, \boldsymbol{k}) = \mu_{\mathrm{t}}(\omega, \boldsymbol{k})\frac{\boldsymbol{k} \times (\boldsymbol{H} \times \boldsymbol{k})}{k^2} + \mu_{\mathrm{l}}(\omega, \boldsymbol{k})\frac{\boldsymbol{k}(\boldsymbol{H} \cdot \boldsymbol{k})}{k^2}.$$

According to these expressions, $\varepsilon_{\mathrm{l}}(\omega, \boldsymbol{k})$ and $\mu_{\mathrm{l}}(\omega, \boldsymbol{k})$ give the medium response to longitudinal electric ($\boldsymbol{E} \times \boldsymbol{k} = 0$) and magnetic ($\boldsymbol{H} \times \boldsymbol{k} = 0$) fields, while $\varepsilon_{\mathrm{t}}(\omega, \boldsymbol{k})$ and $\mu_{\mathrm{t}}(\omega, \boldsymbol{k})$ describe the response to transverse electric ($\boldsymbol{E} \cdot \boldsymbol{k} = 0$) and magnetic ($\boldsymbol{H} \cdot \boldsymbol{k} = 0$) fields.

1.1.3 Temporal and spatial dispersion in metals

In the general case, both tensors ε_{ij} and μ_{ij} depend on the frequency ω and the wavevector $\boldsymbol{k}$. Eventually, any electromagnetic pulse disperses by propagating in the medium, as the Fourier components

$$G(\omega, \boldsymbol{k})\mathrm{e}^{\mathrm{i}(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t)}$$

with different ω and $\boldsymbol{k}$ (that comprise the pulse in accordance with the Fourier transform) propagate with different phase velocities ω/k. Thus, materials with properties that exhibit frequency and wavevector dependence are *dispersive*. The frequency dependence of the tensors ε_{ij} and μ_{ij} describes the *temporal dispersion* of electromagnetic fields, while the wavevector dependence gives the *spatial dispersion*.

In the optical range, metals feature very strong temporal dispersion. It arises due to the inertia and friction of electrons in metals that make the polarization and magnetization inertial with respect to electric and magnetic fields. Thus, the metal's response at a given moment t is dependent on the values of the electric and magnetic fields at all preceding moments $t' \leq t$.

The time interval $\tau = t - t'$ for which the previous history still has a significant effect is defined by the metal's characteristic frequencies ω_{s}. It is obvious that, for electromagnetic fields oscillating at a very high frequency $\omega \gg \omega_{\mathrm{s}}$, the electrons do not have enough time to form any significant polarization and magnetization. Eventually, this results in very weak temporal dispersion with

$$\varepsilon_{ij}(\omega \to \infty) = \delta_{ij}, \quad \mu_{ij}(\omega \to \infty) = \delta_{ij}.$$

However, at frequencies ω below or close to the characteristic frequencies ω_{s}, the temporal dispersion increases and becomes significant.

In general, the characteristic frequencies ω_{s} are different for electric ($\omega_{\boldsymbol{E}}$) and magnetic ($\omega_{\boldsymbol{H}}$) properties of metals. For diamagnetic and paramagnetic metals, the magnetic characteristic frequencies $\omega_{\boldsymbol{H}}$ usually lie far below the optical range, while the electric frequencies $\omega_{\boldsymbol{E}}$ vary from the near infrared to the ultraviolet [2]. Therefore, most diamagnetic and paramagnetic metals lose their magnetic properties early, before reaching the optical range. Thus, starting from the optical frequencies, they feature

$$\mu_{\mathrm{t}} = \mu_{\mathrm{l}} = 1, \tag{1.19}$$

with the temporal dispersion given by $\varepsilon_{ij}(\omega)$.