Loss in metamaterials and nano-plasmonics and potential means of its mitigation

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Abstract

We consider the origin of the loss in the metamaterials, how it scales with size and wavelength and how it can be mitigated by gain, using dispersive dielectrics, or synthesizing novel materials on atomic level.

1. Introduction

Recent years have seen staggering growth of interest in using nanostructured metals in optical range with the goal of enhancing linear and nonlinear optical properties or even engineering entirely novel optical materials unknown in Nature. After the initial heady years of excitement the community is starting to recognize that loss in the metal is an important factor that might impede practical application of plasmonic and metamaterials devices, be it in signal processing, sensing, imaging or more esoteric applications like cloaking. Attempts are being made to "design away" the loss, compensate it by gain, or find new lossless materials. In this talk we examine these concepts one by one and find that they all have their limitations, yet the situation is not without hope.

2. Physics of absorption and refraction in metals at optical frequencies - damping rate is frequency dependent.

The heavy impact of metal losses on the performance of metamaterials has been a subject of lively discussion in the literature but to the best of our knowledge, that discussion did not go back to the basic physics of metals and too often Drude theory, which works remarkably well for the DC-to-RF region, has been used to describe both absorption and refraction. In the first part of this talk [1] we describe a straight-forward theory of optical properties of metals based on Fermi golden rule and show that while refractive (real part of ε) properties are described perfectly well using only the states near the Fermi level, the absorptive (imaginary part of ε) properties depend strongly on the density of states all over the Brillouin zone. As a result, the damping rate γ is a very strong function of frequency, thus metals that are good conductors (low losses in RF) like copper may have losses in optical and near IR ranges, while relatively poor conductors like Al may have low losses in optical range. Using density of states argument we also elucidate the reasons behind the fact that highly doped semiconductors may have lower losses than noble metals in the mid-IR range. Furthermore, we explain while absorption at room temperature does not get significantly decreased at low temperature, quite unlike RF resistance.

3. Scaling of the loss in sub-wavelength metallic structures with frequency and size – the shape and size do not matter for true sub-wavelength designs.

ISBN 978-952-67611-2-1

Next we approach the issue of how the loss in the metal-dielectric structures scales when the electric field gets concentrated on the scale well below wavelength [2]. Using simple energy conservation arguments we show that since in optical range, defined as $\omega \geq \gamma$ the magnetic field in true sub-wavelength structures becomes negligibly small, such concentration can be achieved only when significant part of energy is stored in the form of kinetic energy of mobile carriers which makes such structures inherently lossy. In fact we show that the energy loss rates in true sub-wavelength in all three dimensions structure approaches γ. At the same time, at lower frequencies, $\omega \leq \gamma$ i.e. from DC to far IR the magnetic field sufficiently large can be generated to keep energy our the metal and the losses low. Therefore, we come to a rather simple yet powerful conclusion – once the optical field gets concentrated on sufficiently sub-wavelength scale in all 3 dimensions the loss settles at the same value, equal to the damping rate in the metal, i.e. of the order of 10^{13} s^{-1} no matter what exactly are the size and the shape. We then demonstrate the correctness of this statement using diverse examples of metal ellipsoids, SRR's, short range plasmon-polaritons (SPP) and hyperbolic materials.

4. Can gain mitigate and cancel the loss for the surface plasmon polaritons?

The loss for the tightly-confined SPP whose wave-vector exceeds the wave vector of photon in a dielectric by at least factor of two exceeds 10^{13} s^{-1} and the only way to reduce this loss is to introduce optical gain in the nominally dielectric layer. From the practical point of view only the electrically-pumped gain makes sense, hence one should consider an SPP on the boundary of a metal and semiconductor. In this part of the talk [3] we estimate the value of the population inversion density required to compensate the loss and find that this density is reached when the density of the carriers injected into the semiconductor medium is of the order of few times 10^{18} cm^{-3} for Ag and 10^{19} cm^{-3} for Au. These densities are high but not unrealistic. Indeed they can be attained in the normal semiconductor waveguide structure, where the recombination time is on the order of 10^{-10} s. Unfortunately in the tightly confined SPP the radiative recombination rate gets strongly enhanced by the Purcell effect due to high density of SPP states in the vicinity of SP resonance. Purcell effect can reach value of 100 and more with the ensuing reduction of radiative recombination time to less than 10^{--12}s. Therefore the injection current density required to maintain gain grows by a factor larger than 100 and for very tightly confined SPP's reaches unsustainable values of $1MA/cm^2$ and more. It is rather ironic that Purcell effect that is so beneficial in enhancing spontaneous processes like photoluminescence and Raman scattering becomes a deleterious factor in plasmonic interconnects. In the end, our conclusion is that one cannot compensate the loss in plasmonic interconnects with tight confinement and only long range plasmons with weak confinement are practical.

5. Spaser as a single mode laser – does it work?

Our next step is to consider the SPASER – a device in which electron-hole pairs recombine and emit coherent surface plasmons. For this to take place the gain of the SP mode should exceed the combined radiative and non-radiative loss. Previously it had been shown that the semiconductor gain can exceed the modal loss when the carrier density approaches few times 10^{18} cm^{-3} for Ag. But SPASER has just a single mode hence not only stimulated but also a spontaneous emission enhanced by the Purcell effect gets emitted in the same mode and thus the input-output characteristic of spaser is linear with no evidence of threshold. The only way to determine the threshold is to consider the linewidth of SP emission which exhibits narrowing as the coherence increases to larger number of SP emitted via stimulated rather than spontaneous emission. We develop a set of equations governing linewidth and SP density as a function of pump current density and define the "SPASING" threshold as the value of pump current at which the linewidth gets reduced by a factor of two. We then obtain the most interesting result that states that for the true sub-wavelength SPASER the threshold current is simply is always equal to $e\gamma$ where e is the electron charge and γ is the damping rate in the metal, i.e. the threshold current is about 8μA for Ag and 15μA for Au, no matter what semiconductor gain material and what geometry is used. While the value of threshold current is reasonable the threshold current density for the few tens of nanometers SPASER becomes unsustainably high, in excess of 1MA/cm^2. Hence while strong and very efficient emission into the SP mode can be achieved, the emitted plasmons are not coherent with each other and one cannot call the process Spasing. On the other hand for many practical applications coherence is not necessary and "SPED" (Surface Plasmon Emitting Diode" may be a useful device.

6. Reducing the loss with highly dispersive dielectric

In this part of the talk we consider a rarely discussed situation of having a SP in the structure combining a metal with highly dispersive (resonant) dielectric. We then show that near the dielectric resonance most of the energy is stored inside the dielectric (essentially in the oscillations of bound electrons) and since a smaller fraction of energy gets inside the metal the effective loss gets reduced. We shall discuss the practical means of implementing such structures using resonant metal atoms or quantum dots and make a rather interesting connection with the slow light propagation in dielectric medium.

7. Can a lossless metal be engineered?

Having exhausted the more obvious ways of loss mitigation we now return to the original physical picture of light absorption inside the metal and note that according to Fermi golden rule the absorption can only take place between two real physical states in the metal separated by energies equal to that of the photon. Then it is not difficult to make an observation that if the conduction band is sufficiently narrow and separated by wide band gaps from the other bands a situation may occur in which there will be no way for the electron to make a transition from an occupied to unoccupied state and hence there will be no absorption. We consider such a hypothetical method using a tight-binding model and discover that for a wide variety of elements the "lossless metallic" situation can occur in near IR when the distance between neighbouring atoms is close to 1nm, i.e. much larger than in real atoms. That is why no lossless metals occur in Nature, however, if the atoms can be held at this distance inside some dielectric matrix the lossless metal may be synthesized one day. In this talk we shall discuss a few more promising artificial materials with reduced losses.

8. Conclusions

Our conclusion is that metal losses cannot be easily engineered away of compensated by gain and one can either concentrate on applications where loss is not a serious impediment (such as sensing), look at structures that are comparable to wavelength at least in one dimension, or try to synthesize new artificial materials on the atomic level

References

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