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Overcoming Losses in Metamaterials

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Abstract **-**Periodic loading of waveguides was introduced in the 50's and Man-made Superlattices in the 70's, which have metamorphosed into metamaterials. Now, we have metamaterials, combining the two features into something truly phenomenal mainly because the advent of nanotechnology allowing the concept of circuit elements to be applied where resonances may be designed in terms of shapes and sizes. However, since the present emphasis involves applications in IR and visible light, the principal new features of metamaterials require forms and symmetry in sizes needing techniques developed in nanotechnology, i.e. involving e-beam and atomic beam lithography. There are fundamental limitations imposed by finite electronic mean-free-paths on conductivity, and short mean free paths exist for phonons from nonlinear potentials. Not much can be done with the phonon scattering, but electron scattering may be reduced. In addition to the use of surface plasmons, the interaction volume may be reduced to the nanometer domain with nanotechnology, inspired by the realization that a single atom may be involved in efficient interactions with light. To deal with phase de-coherence, it is emphasized that the size of the individual elements forming the metamaterials should be below the phase coherence length to avoid de-coherence effects in the metamaterials excited by the incident light.

Keywords**:** Nanoscale plasmonic, coupling of plasmons & atomic states, Bohr radius

1. Introduction

Metamaterials owe their origin from periodic loading in waveguide structures in the 50's (Kirschbaum et al., 1959) and man-made superlatives from the early 70's (Esaki et al., 1970). Now, we are combining the two. Since our present focus involves applications in IR and visible light, the metamaterials need to involve forms and symmetry at the nanoscale. This requires techniques developed in nanotechnology, involving e-beam and atomic beam lithography. We form bulk materials by periodicity to gain volume of interactions. Much more unique to metamaterials is that their elements consist of shapes and sizes of meta-atoms inspired by LC networks in circuits, with their main attributes coming from resonances. In addition, the symmetries and forms, together with the involvement of hetero-junctions of solids, allow for combining of metamaterials with superlattices as a new area of man-made materials. However, RPA, Random Phase Approximation, generally used to describe lossy coupled harmonic oscillators for high electronic losses for spatial averaging is still needed, via the Ergodic principle, with time averaging. Not much can be done with the phonon scattering, other than lowering the ambient temperature. Current methods to avoid de-coherence effects from electron scattering is to employ extremely thin layers of metal such as gold by restricting interaction to surface plasmons. It is a standard procedure to avoid heavy optical losses by avoiding any interaction between metals such as gold and silver with thickness more than the skin depth. In this manner, the interaction only takes place on the surface, avoiding phase decoherence as result of plasmonic interactions between the incident light and the interacting metallic medium of gold or silver (West et al., 2010). It is well known that the interaction of light with a single H-atom with a quality factor Q = 24.8 x 10^6 means that the 1s-2p transition requires 25 million cycles of the incident field. There is an analogy to be made between metamaterials and a single atom. The high scattering rate of electrons may be controlled by confining interaction at most tens of Å units, within sizes represented by several nanometer range, such that the whole structure is below the finite scattering length to eliminate any loss of coherence from the plasmon interacting with the incident photons (Tsu and Fiddy, 2012 and 2013). In other words, the entire structure for interaction between the incident photon and the plasmonic structure should have size no greater than several tens of Å. Although with the use of surface plasmons, some high losses may be by-passed, however, more can be done using nanostructures with the limiting range of interaction to sizes characterized by nanotechnology, e.g. with interaction within a volume represented by the structure no greater than few tens of Å, eliminating any possible de-coherence scattering, even though confined to the surface. To summarize, the whole structure involving plasmonic interaction of the metallic structure should be no more than few tens of Å, thereby completely eliminating any possibility of de-coherence interactions of the metamaterial structure with the incident light, by having the size smaller than any randomizing scattering. Obviously such small structure requires the use of nanofabrication!

There is further insight to be gleaned from comparisons with the single H-atom and the Bohr orbit forming a sphere with a single electron and with the density used in the computation of the plasma frequency when equal to the 1s-2p transition. In fact in references by Tsu and Fiddy (2012 and 2013) the sphere size used was 0.6Å, rather than 0.53Å, which is the Bohr orbit. In searching for this measure of the near field trapping, we discovered an error in Tsu and Fiddy (2012 and 2013), seemed trivial, as we shall see, very important, forgetting that the plasma frequency includes a dielectric constant in the denominator. It was found that increasing the dielectric constant from 1.0 to 1.2, the sphere size with a radius of 0.6Å drops back to 0.53Å, the Bohr radius. An increase of 20% for the atomic dielectric constant of H-atom, from 1 to 1.2 is consistent from what was derived, for the case of the dielectric constant of nano-particles of Si (Tsu and Babic, 1994) (Tsu et al., 1997). With this increase of the dielectric constant, the trapping is within the H-atom itself, rather than some near-field trapping! We have obtained a better understanding with this correction, the ground state of the atomic system having an effective orbit size with a slight increase of the dielectric constant, the plasma frequency is indeed equal to the 1s-2p transition. With this new understanding, we are able to move forward for any atom or meta-atom interacting with photons. ***The field trapping is due to the increased dielectric constant resulting in keeping the electron, or electrons, confined by the increased dielectric constant over the environment.*** Furthermore, lowering the individual size of the interaction unit to ~ 10-20Å allows each individual interactions free from randomizing scattering. Nevertheless, as pointed out with reference to the Ergodic Principle, the totality of all these individual units may still be summed in their overall interacting with light represented by RPA, or an effective medium, if anything more than single spices are involved.

2. Discussion

(A) Optical losses are extremely high whenever light is interacting with conduction electrons in metals. Metals have Avogadro’s number of electrons, taking the energy from light via Landau Damping, and electrons further transfer their energy to phonons, both optical and acoustic (Tsu, 1967). It is important to note that even with nano-sized volume of interaction, phonons are still involved because these meta-elements are deposited on some substrate materials.

(B) In III-V and II-VI materials, carriers come from doping, which are several orders of magnitude below the number in metal. However, direct Coulomb scattering from charged donors and acceptors in compounds such as Si, GaAs, CdS, etc. again give rise to efficient Coulomb scattering thereby randomizing the phase, something which should be avoided completely.

(C) What we learn from Single Atom Trapping of Photons: we found from the interaction with a weak background, that light is trapped within the Bohr radius of a single H-atom, having trapping time of 10^{-9} s, corresponding to 2.45 x 10^{7} cycles of the incoming electromagnetic wave resulting in the 1s-2p transition of the H-atom. We were able to explain that the trapping in our case takes place within the Bohr radius, which is not the same as the case of small antenna given by the Chu-limit (Chu et al., 1948).

(D) More than 35 years ago, when it was discovered that Laser Annealing using high power pulses resulted in ordering, apparently without melting. Some constitutive relationships, more than just the piezoelectric constants, are needed to represent the couplings (Tsu and White, 1965) (Tsu and Jha, 1980). It should be apparent that physics is based on constitutive equations, in addition to those basic equations such as Schrodinger and Maxwell equations, which can hardly represent couplings by themselves. In this case, there is need to describe coupling between a single atom, such as 1s and 2p states, with the fields of the incident photon, having interaction taken place in the trapping site represented by the Bohr orbit. Although Bohr orbit has been shown incorrect as far as the prediction of an orbital angular momentum. However, as we have shown that the common region of interaction where the electron of a single H-atom, represented by an electron in 1s state interacting with the incident reactive fields, the oscillating electric fields of the photon trapped within the Bohr radius. In Fact we came to this correct representation after failing to apply the usual Near-Field Trapping. Too summarize, the trapping is within the Bohr orbit, because the plasma frequency is the same as the 1s-2p transition.

(E) For metamaterials, we are in luck, because their 2-D or 3-D design is entirely under our control. Our approach is to distinguish their properties from what we have learned about solids with atoms so close that we represent them using RPA, or an effective medium model. Now, we propose placing each individual atom or meta-atom far apart, i.e. more than 10 Å apart, such that units are not coupled in forming an effective medium, but close enough to be integrated into a distinct interaction region. Compare for example, a region of slab or a medium capable of representing a Fabry-Perot interferometer, i.e. collectively representing a cavity for serving as a metamaterial for specific functions, such as a man-made domain for switching, or for amplifications including parametric amplifiers! The combined size of such units would have individual units not more than 10-20 Å in size, but the **totality** of these can indeed be represented by RPA again and rate equations can be used to describe the total number of such units of 10-20 Å size. We thus see a path to avoiding the high losses in a typical solid! As metamaterials with individual atoms, in our present case, the size represented by the dielectric function given by the unit element size should serve to determine the plasmonic frequency. We pick a size, for example, 20 Å. and using the formula for the dielectric function given by Babic and Tsu (Tsu and Babic, 1994) (Tsu, 2011), we can then determine the plasma frequency, and therefore the resonant frequency to match the plasmonic frequency for the metamaterial.

The use of nano-sized gold constitutes our first step towards the use of plasmons in nano-sized metallic components, applied to metamaterials. Beyond that, we intend to try placing InP next to GaN, in the formation of incoherent transfer of electrons from the top of the valence band of InP, via diffusion to the conduction band of GaN. This kind of carrier transfer without doping, ultimately forms a giant step towards integrating metamaterials with carrier transfer via heterojunctions, resulting in systems with controlled variable concentration without Coulomb scattering.

3. Conclusion

To affect high impact metamaterials involving visible light, the excessive electronic losses may be overcome by applying nano-sized features to avoid extremely low mean free path of electrons in metal. The basic discovery involving light interaction with a single H-atom serves as the inspiration for exploiting structures of no bigger than several tens of nanometers, in avoiding high losses to preserve coherence for the electrons involved.

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