Interaction between Nanodevices and Electromagnetic Wave Propagation: Nano-Transmission Lines and Nano-Antennas

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Abstract

This contribution reviews our understanding of the phenomena of electromagnetic wave propagation in nanostructure devices. Recent advances in the field are reviewed and a critical discussion is provided for a wide range of nanodevices including nanowires, nanostructure active devices, single electron device interaction, and quantum devices like quantum dots. An improved understanding of the interaction phenomena is important for the advancement of applications of nanotechnology in various fields of science and technology. Examples for such fields are the addressing and manipulation of quantum dots excited by signals in the microwave up to terahertz frequency range,

Most experimental and theoretical work on the electromagnetic field interaction with nanodevices has concentrated on optical studies and interaction. Various “nano” versions of major optics areas, such as nanophotonics and nanospectroscopy, are developing with increasing rate in the area of focusing and guiding of light on nanometer scales beyond the diffraction limit of conventional far-zone optics. For object imaging, the near-field part of the radiation contains all the information about the scatterer, but at increased distance from the object, the evanescent portion of the scattered field exponentially decays, resulting in loss of information on the “fine” (sub-wavelength) features of the scatterer.

However, recently passive as well as active nanodevices have demonstrated anomalous interaction properties with regards to electromagnetic wave propagation properties. Since the wavelength of microwave and terahertz signals is much larger than the nanodevice itself the interaction might prove complicated and needs to be investigated in full detail. Also many assumptions on wave propagation of electromagnetic waves along transmission lines do not readily apply to nanodevices due to their inherent nonlinear response and the importance of quantum effects in such devices.

It is interesting to note that the charging energy is of the order of 0.1–10 meV for the many nanodevices, such as for example quantum dots made by electron beam lithography, which lies in the same order as energy of radiation at terahertz frequencies. The electronic transport of nanowires can be affected by many factors. The lateral shape varying in space leads to a mixture of different modes in nanowires. If the shape varies slow enough to satisfy adiabatic approximation, the step-like structure of conductance is still preserved but it is totally determined by the narrowest neck part of the whole nanowire. When a nanowire is irradiated under a proper external electromagnetic field many new features arise due to the inelastic scattering by photons. When the Fermi level is below the lowest transverse level in the neck part of the nanowire electrons cannot pass without external field. But under the external field irradiation electrons can absorb energy of photons and surpass this geometric barrier. Therefore, in the regime of the barrier the electron reflection may be induced by the combination effect of the field and the lateral shape variation. However, the pure external field effect on the transport (photonconductance) has not drawn attention yet, and this effect is important for both basic physics knowledge and nanotechnology application.

For practical applications, the operation of active nanotube devices at microwave frequencies has recently been demonstrated. Nanotubes are important devices with potential circuit applications such as passive high frequency components for interconnects, as mixers, detectors, and antennas. However, the electromagnetic properties of nanotubes are currently not well understood. Especially, the utilization of nanotubes as terahertz interconnects and antenna structures has very recently attracted theoretical work on the subject, giving rise to interesting effects such as coupling to surface plasmon polaritrons, left-handed materials, anomalous optical wave propagation etc.

The paper will focus on the general theory and its pitfalls currently employed to study the interaction. The result from this discussion will show areas for further theoretical and experimental investigations. Finally, potential fields of applications will be identified and the availability of the theoretical foundations in this context will be presented.