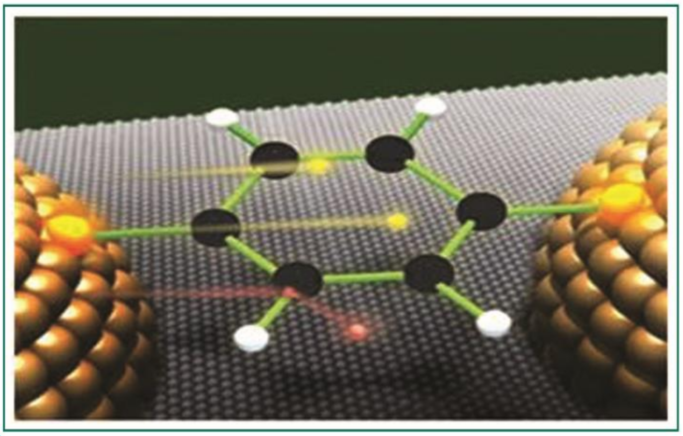
SONA COLLEGE OF TECHNOLOGY

| An Autonomous Institution |

Department of Electronics and Communication Engineering

MICROELECTRONICS TO NANOELECTRONICS

2015-16



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Preface

Microelectronics relates to the study and manufacture (or microfabrication) of very small electronic designs and components. These devices are typically made from semiconductor materials. Many components of normal electronic design are available in a microelectronic equivalent. These include transistors, capacitors, inductors, resistors, diodes and insulators and conductors can all be found in microelectronic devices. Unique wiring techniques such as wire bonding are also often used in microelectronics because of the unusually small size of the components, leads and pads. This technique requires specialized equipment and is expensive.

Nanoelectronics refer to the use of nanotechnology in electronic components. The term covers a diverse set of devices and materials, with the common characteristic that they are so small that inter-atomic interactions and quantum mechanical properties need to be studied extensively. Some of these candidates include: hybrid molecular/semiconductor electronics, one-dimensional nano tubes/nano wires (e.g. Silicon nano wires or Carbon nano tubes) or advanced molecular electronics. Recent silicon CMOS technology generations, such as the 22 nanometer node, are already within this regime.

NANOELECTRONICS BASED INTEGRATED ANTENNAS

Haripriya.S – IV Year

Nano electronics is the gateway to a variety of novel electronic devices and systems with substantially new properties. It enables the development of nano scale electronic devices, covering radio frequencies in the terahertz range and beyond up to optical frequencies. The on-chip integration of antennas opens new vistas for novel devices and integrated systems for sensing, detection, wireless communications, and energy harvesting applications. However, the requirements of antenna integration into the chip architecture are different from those of circuit integration. Nano electronic technologies strike a compromise between these requirements. Today, silicon and silicon-germanium-based monolithic integrated millimeter-wave (mm-wave) circuits already facilitate the realization of communication and sensing systems operating at frequencies up to the mm-wave range. In the near future, Si based integrated circuits (ICs) will open up new perspectives in communication and sensor technologies. In this context, monolithic integration of antennas contributes significantly to the compactness of front ends and avoids lossy and expensive cable connections between circuitry and antennas. At mm-wave frequencies and beyond, the antenna dimensions are small enough so that even antenna arrays may be integrated monolithically. Besides developments in semiconductor technology, the emerging possibility for integration of antennas within future nano electronic device platforms based, for example, on polymer materials, carbon nanotubes (CNTs), graphene, superconductors, or plasmonic devices, opens up interesting perspectives. The electronic properties of some materials will allow an extreme miniaturization of antennas. For physical reasons, frequencies ranging from the terahertz region up into the optical region require close integration of the active or rectifying device. Furthermore, in some cases, the electronic properties of the antenna material and structures are essential for the operation of the antenna. Examples for this are CNT antennas, nanowire antennas, plasmonic antennas, and some metallic and superconducting antenna structures. We distinguish between nano electronics-based integrated antennas and nano antennas. The former are motivated by the requirements of a nano electronic monolithic IC or system-on-chip. Nano antennas are nanostructures themselves. The design of nano electronic systems on-chip with integrated antennas or nano antennas should be performed by combining methods of antenna design and nano electronic device design.

Physical Constraints in Antenna Integration

The monolithic integration of antennas imposes severe restrictions on the chip area used by the antenna. In order to clarify the requirements for the monolithic integration of the antenna, it is necessary to consider the fundamental physical limitations of antennas. In1948, L.J. Chu discussed the physical limitations of omnidirectional antennas showing that an antenna embedded in a virtual sphere with diameter 2a, and hence, exhibiting a maximum dimension of 2a, has a potentiality of a broad bandwidth under the condition that the antenna gain is equal or less than 4a/l . Physical limitations of bandwidth, gain, and directivity have been derived for antennas of arbitrary shape. Super directivity antennas, however, require extremely high currents to produce only a small radiation field. Integrated nano electronics-based antennas provide interesting possibilities for short-range data transfer such as wireless chip-to-chip or intrachip communication. Wireless on-chip communication and chip-to-chip communication may be a solution to the increasing complexity and density of interconnect structures of monolithic ICs. Ultra wide band (UWB) technology offers high data rates over short distances without suffering from the multipath interferences and, therefore, will be suitable for this purpose. Chips may include planar antenna structures, forming a multiple-input and multiple-output (MIMO) system. MIMO transmission provides a significant increase in data throughput and link range without additional bandwidth or transmit power due to its higher spectral efficiency and link diversity.

Figure 1 shows a wireless MIMO channel model where each receiving antenna RX1cRX3 receives the signal of every transmitting antenna TX1cTX3.

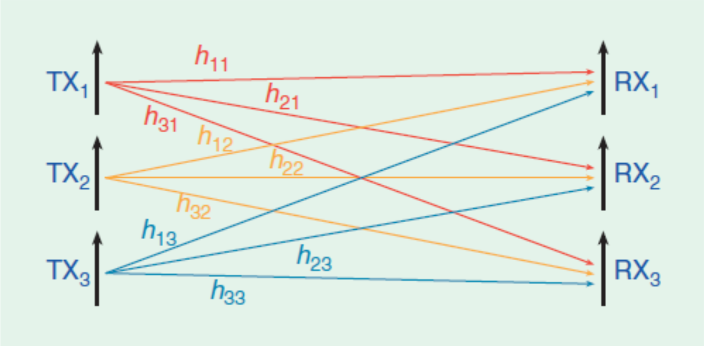


Figure 1. *The wireless MIMO channel model.*

Figure 2 shows two chips, each with several antenna elements.

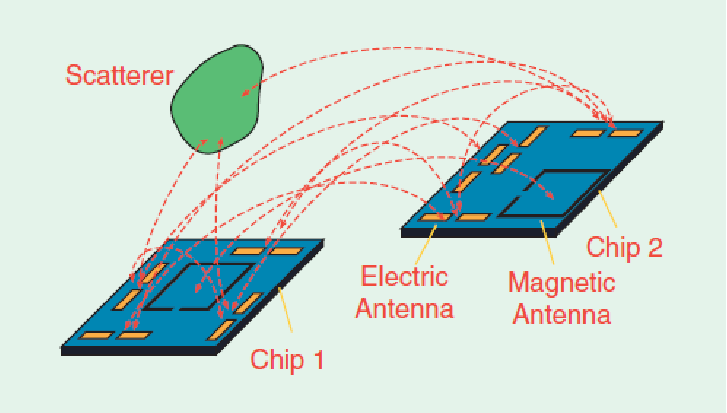


Figure 2. *Interchip and intrachip MIMO communication.*

The mutual electromagnetic coupling of the antenna elements occurs both between the antenna elements of a chip and between the antenna elements of different chips. The electromagnetic coupling can be performed via waves radiated into space and surface waves along the chip surface. The coupling also is affected by the housing assembly and by scattering bodies. If the antennas at one side of the transmission link are confined within a limited space, the maximum number N of useful channels according to is limited by

$$N = 8\pi^2 \frac{a^2}{\lambda^2},$$

where a is the radius of the smallest sphere enclosing the antennas at the ends of the link.

The Shannon information capacity of space-time wireless channels formed by electromagnetic sources and receivers in a known background medium is analyzed from the fundamental physical point of view of Maxwell’s equations. For a given additive Gaussian noise model, the information capacity is bounded, depending on the spherical volume enclosing the receiver antennas. The channel matrix used in the information theoretic context can be derived from multiport circuit models. This channel matrix can have full rank and therefore support multistream transmission, even if the antennas are densely packed. This work is of fundamental importance for the realization of chip to chip transmission links.

MONOLITHIC INTEGRATED ANTENNAS

MUKILMOZHI – IV YEAR

Today, silicon is the most interesting basic material for the monolithic integration of antennas. The monolithic integration of antennas has to be realized in such a way that the electromagnetic wave is emitted with high efficiency, is attenuated through the substrate as little as possible, and does not excite substrate waves. Since monolithic integrated antennas on the chip area are in close proximity to the circuitry, and even sometimes share an area with it, the design of the IC has to be such that the antenna radiation field does not interfere with

the guided waves in the circuits and interconnects. Silicon as a substrate for mm-wave monolithically ICs has been suggested in 1981, when no one believed in the applicability of silicon in this frequency range, by the RCA group of A.

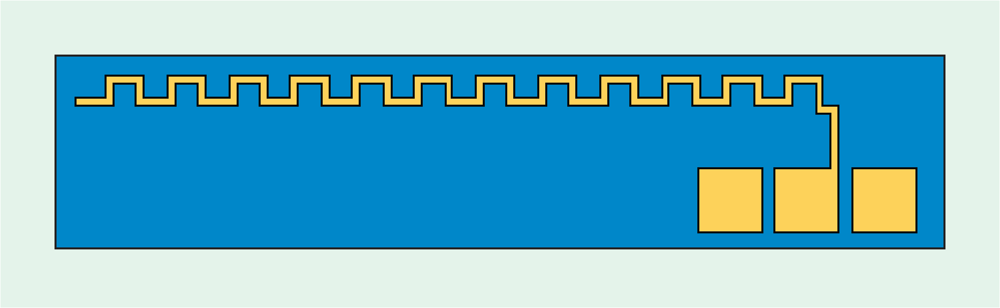


Figure 2. Interchip and intrachip MIMO communication.

There have been research activities since 1985 in the field of silicon mm-wave ICs (SIMMWICs) at the former AEG-Telefunken Research Institute (which became the Daimler Research Center) and at the Technische Universität München . It has been shown that high-resistivity silicon with a resistivity greater than 2,000 V# cm is excellently suited for monolithic integration of RF circuits at frequencies above 40 GHz since substrate losses can be neglected in comparison with skin effect losses and radiation losses. Planar transmitters and receivers for frequencies up to 100 GHz with integrated antenna structures have been realized. The requirement to use high-resistivity silicon as the substrate for fabricating distributed passive circuit structures and antennas determines the design philosophy of SIMMWICs. Today, a vast literature exists on monolithic integrated antennas. Using a 0.18 mm CMOS copper technology, a 15 GHz on-chip wireless interconnects system, integrating antennas in digital CMOS circuitry facilitating wireless clock distribution over the chip. A 15 GHz intrachip wireless interconnect using integrated antennas consisting of a transmitter-receiver pair can be fabricated in 0.18 mm CMOS technology. A 15 GHz sine wave was transmitted from an on-chip 2 mm long zigzag dipole antenna and received by a zigzag dipole antenna located 2.2 cm away. An intrachip wireless interconnect system using meander monopole on-chip antennas and operating in a frequency band from 22 GHz–29 GHz. On-chip UWB radios in that frequency band are discussed. The on-chip antennas are meander monopoles with 1 mm axial length, as depicted in

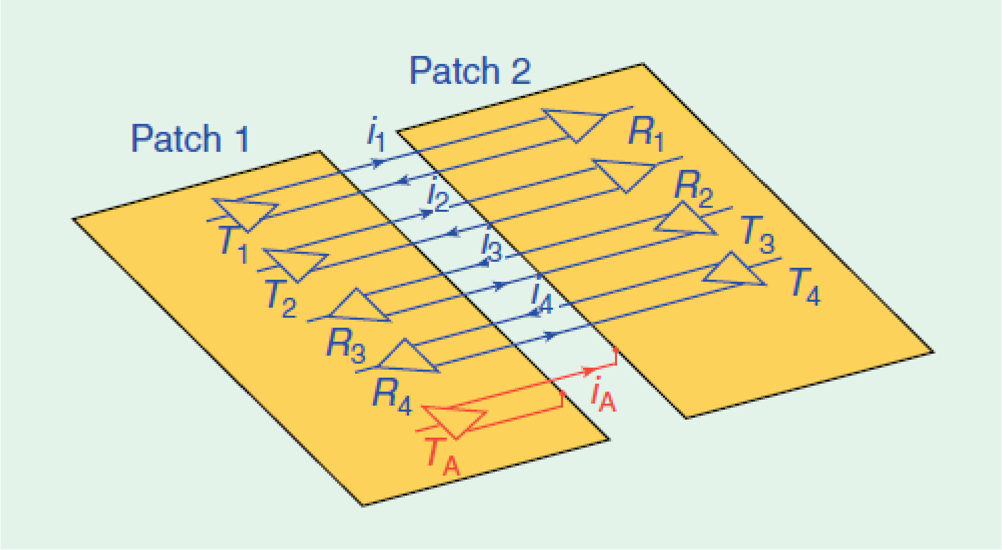


Figure 3 Monopole antennas

Monopole antennas have been fabricated on high and low-resistivity substrates and measured up to 110 GHz. Measurements of monopoles at frequencies up to 110 GHz have shown that antennas on high resistivity substrates have a much higher transmission coefficient than those on low-resistivity material. One problem in monolithic integration of antennas is the high chip-area demand of antenna structures, which would drive up the costs of chips with integrated antennas. This allows for optimal usage of chip area, as the antennas share the chip area with the circuits. Care should be taken that the interference between the antenna field and the field propagating in the circuit structures stays within tolerable limits. The structure represented schematically in Figure 4 contains two antenna patches. Both antenna patches serve as the ground planes of the circuits.

These circuits contain line drivers T1cT4 driving over symmetrical interconnection lines the line receivers R1cR4. Furthermore, there is a driver TA, the output of which is connected to both patches: however, only one conductor bridges the gap between the patches. The sum of the currents i1ci4 flowing in both directions through the transmission line modes vanishes and is not exciting the antenna. On the other hand, the current iA excites an antenna radiation mode. The circuit for this current is closed via the displacement current in the near-field of the antenna. By exciting the interconnection structures in transmission line modes and the antennas in antenna modes, the interference between circuit and antennas can be minimized. We don't need to use differential lines between the patches. Any arrangement of N conductors guiding N21 transmission line modes can be used. In general, an interconnection structure consisting of N conductors can guide up to N21 quasi-transverse electromagnetic transmission line modes and one antenna mode. Figure 5 shows schematically the realization of this principle in silicon technology [32], [33]. The IC is fabricated on a high-resistivity silicon substrate ($1k V # cm) of 650 mm thickness. The substrate is backed by a metallic layer. On top of the substrate, a low-impedance layer (< 5V # cm) of 5 mm thickness is grown. TheCMOS circuitry and the interconnects are embedded in this top layer. The low-resistivity top layer is required to achieve circuit insulation. The electromagnetic field of the circuits is mainly confined in this top layer. The antenna field is spreading over the whole thickness of the substrate. Due to the high resistivity of the substrate, the antenna losses are low. Since only a small fraction of the antenna near-field energy is stored in the low-resistivity layer, the coupling between the antenna near-field and the circuit field is weak. Furthermore, the interference between the CMOS circuits and the antenna field can be reduced when the main part of the circuit is operating in a frequency band distinct from the frequency band used for the wireless transmission.

The current distribution in both patches mainly is concentrated in the neighborhood of the slots. The antenna behaves as an open-circuited slot antenna. The guided wavelength

is in the range of 1 mm. The open-circuited slot with a length of about 1 mm is a transmission line resonator with a resonance frequency in the V-band. The standing wave in the slot excites the radiation field.

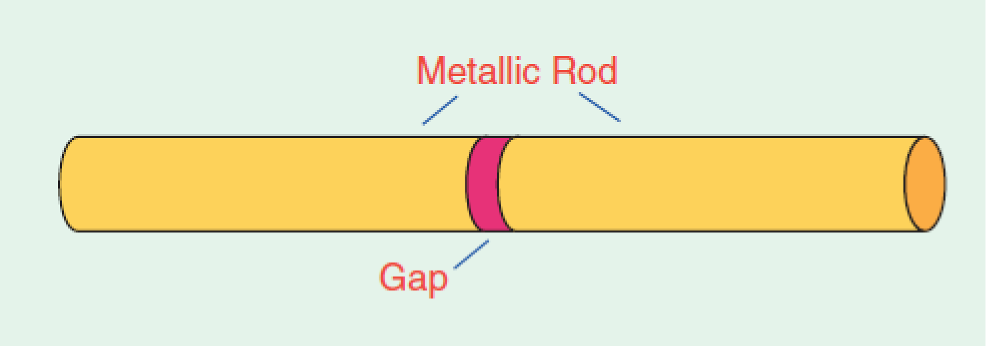
The measurements have been performed for two antenna alignments where the antennas were positioned in each other's radiation minima and maxima. Both cases were investigated on-wafer and for diced chips. The chip-to-chip links show greater insertion loss due to the reflection on the substrate-free space interface. The worst-case transmission link gain-chip-to-chip link in the direction of minimum radiation shows an insertion loss of –47 dB, which is sufficient for high-rate data links. Integration of Antennas with Metal-Oxide-Metal Diodes A promising novel concept for infrared (IR) detectors is the combination of a nano antenna with a rectifying element. The rectifying element extracts a dc component from the rapidly varying current delivered from the nano antenna. Semiconductor diodes are widely used, but they encounter frequency limitations for the mm-wave and long-wave IR regime. It has been demonstrated that MOM tunnel diodes can provide rectification for IR and even optical radiation. Such MOM diodes are formed naturally at the overlap area between two antenna arms, for example, for a dipole antenna. The early work focused on symmetrical MOM diodes, that is, diodes with the same metal for both electrodes (antenna arms). Such symmetrical MOM structures result in symmetrical current-voltage characteristics, and they need to be biased away from the origin of the I–V curve in order to yield a nonlinearity needed for rectification. This results in extra detector noise due to the bias and added circuit complexity. Recent work has shown that asymmetrical MOM diodes can be formed by metal combinations with different work functions, such as platinum and aluminum, and the resulting asymmetrical I–V curves posses the required nonlinearity for zero bias. An important issue for rectification at IR frequencies is the time constant of the rectifying element. For detection of 10 mm long-wave IR radiation, the rectifying element has to be able to respond to 30 THz antenna currents. For a typical antenna resistance of 100 V, this limits the tunnel-diode capacitor area to less than 100 nm 3 100 nm, which is challenging for fabrication. Recent work has demonstrated e-beam lithographically defined dipole antenna structures with integrated MOM diodes that showed the expected polarization response and antenna-length dependence of dipole nano antennas for 10 mm long wave IR radiation

ANTENNAS IN PLASMONIC DEVICES

Sinthanai Selvi – IV Year

Plasmonics deals with unique properties of metals at optical frequencies to guide and manipulate light signals at the nanoscale. At optical frequencies, a local electric field oriented parallel to a CNT or a thin metallic wire with a diameter in the order of some nanometers can affect a local charge separation and generate quasi particles resulting from the quantization of plasma oscillations.

Figure shows the schematic of a nanoscale plasmonic optical antenna consisting of a metallic rod with a small gap in the center filled with a different material .



The antenna concentrates the received optical energy in this feed gap and yields a strong interaction with the material in the gap. The time-varying electric field due to the incident light wave can exert a force on the electrons inside the metal and drive them into a collective oscillation, known as a surface plasmon. Depending on the application, the gap can be filled by semiconducting or nonlinear metal, but also by single molecules, DNA, or protein. Even moderate illumination yields high plasmonic field intensities. Therefore, nonlinear devices for frequency conversion and high-speed optical switching may be realized. With semiconductors in the gap, ultrafast, low-noise photodetectors could be realized. A silicon nano photodiode with a surface plasmon antenna for a large-scale integrated chip is described. A surface plasmon resonance structure is used to achieve an efficient light coupling and short response time. A silicon oxynitride (SiON) waveguide integrated structure is applied to feed the light into periodic nano scale metal-semiconductor-metal Schottky electrodes, operating as a plasmonic optical antenna. Chip-scale optical interconnects are proposed where optical antennas are used to bridge the gap between microscale dielectric photonic devices and nanoscale electronics.

A resonant optical monopole nano antenna positioned at the end of a metal-coated glass fiber near-field probe is in Figure - the scanning electron microscope images of this antenna. The base of the nano antenna is a fiber-optic probe whose sharp glass tip has been made by heat-pulling of the fiber. The fiber has been coated by evaporation with a few nanometer thick chromium adhesion layers, and, upon this, comes a 150 nm aluminum coating. The monopole aluminum nanoantenna of 50 nm width and 20 nm curvature radius has been fabricated by focused ion beam milling. The antenna is excited by the near field of the fiber probe. The antennas have been modeled using CST Microwave Studio.

Figure shows the antenna resonances for a wavelength l5514 nm and variable antenna length. The simulations have been validated by single molecule fluorescence measurements.

By coupling a poly[2-methoxy-5-(2'-ethyl-hexyloxy)- p-phenylene vinylene] (MEH-PPV) polymer to resonance- tuned silver nano antenna arrays, the enhanced photoluminescence of the MEH-PPV/silver nano antennae due to an energy transfer effect in the surface plasmon resonance coupling between the MEH-PPV and silver efficient solar cells for photon harvesting.

Bowtie nano antennas consisting of gold triangles with triangle lengths of 75 nm and gaps ranging from 16 nm to 488 nm have been fabricated and investigated in [48]. Figure 16 shows two samples of bowtie antennas with gaps of 20 nm and 285 nm. The Au films are 20 nm thick with a 5 nm Cr adhesion layer and were deposited onto an indium tin oxide coated fused silica coverslip. Optical excitation of the bowtie structures excites the plasmon resonance of the structure, which could be sensed in the wavelength dependence of the scattering spectra.

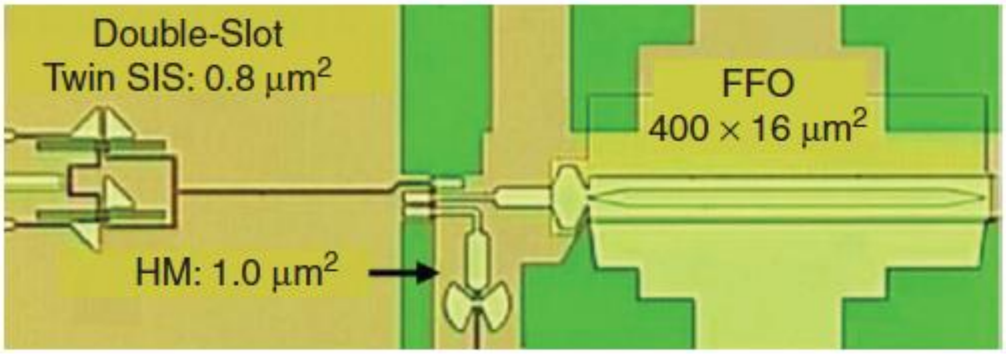
SUPERCONDUCTING ANTENNAS

HAJA KAMALUDEEN.J – IV Year

Using superconductors allows the realization of superdirectivity antennas, addressed in the “Physical Constraints in Antenna Integration” section, of extremely small size. Furthermore, there are numerousinteresting applications of superconductors for antennas. Superconductors show superior properties, such as low power loss, low attenuation, and low noise level. Superconductors allow us to realize extremely small antennas that exhibit a high radiation quality factor. Superconducting antennas are well suited for the combination with Josephson-effect-based radiation detectors. Superconducting quantum interference devices (SQUIDs) are extremely sensitive magnetic field sensors and active magnetic antennas applicable from dc to several 100 MHz. An electrically small active antenna for the frequency range 50–500 MHz, consisting of a YBa 2Cu 3O7 half-loop plane antenna and a 200 element SQUID array amplifier.

A mixer using a super conductor insulator- superconductor (SIS) quasi particle structure is integrated with a double-dipole antenna. The receiver operates at 500 GHz, 550–650 GHz, and 1.8 THz. This single-chip superconducting integrated receiver has been developed for the

Terahertz Limb Sounder (TELIS) balloon project and is intended to measure a variety of stratosphere trace gases is presented.



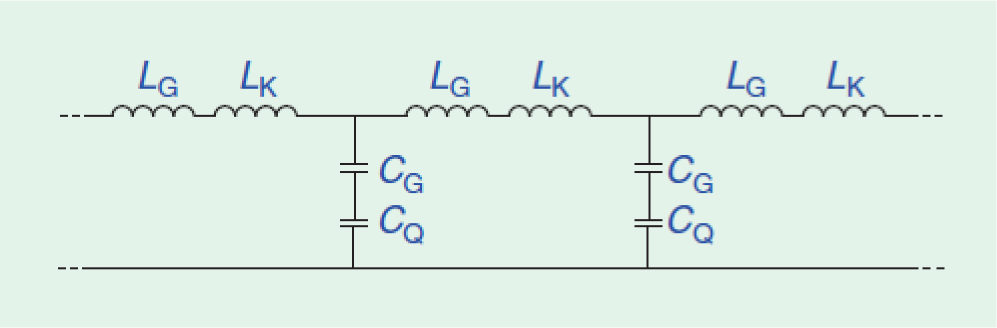
By exciting a bow-tie antenna structure of a high temperature superconducting YBa 2Cu 3O 72d thin film dipole antenna on MgO substrate with 100 fs, 750 nm laser pulses, the radiation of terahertz pulses from the bow-tie antenna could be affected. Hot-spot generation in the superconductor allows fast and ultrasensitive optical detection. A photon incident on a superconducting nanowire or nano ribbon yields a temporary generation of a resistive barrier across the nanowire or the nano ribbon and results in a voltage pulse. The decay time is in the order of 30 ps. Superconducting nanowire single photon detectors exhibit broad wavelength response, short reset time, and low noise and, therefore, are promising candidates to replace other single photon detectors, like avalanche photodiodes in applications such as free-space optical communications, quantum cryptography networks, and quantum computation. Superconducting niobium nitride (NbN) nanowire single-photon detectors with silver optical antennas for free-space coupling were designed. 100 nm wide NbN nanowires with 200 nm pitch on sapphire substrate are used. Light of 1,550 nm wavelength is incident from the bottom through the antireflection coating (ARC). Simulation results have shown a light absorption as high as 96% for TM polarization.

CARBON NANOTUBE ANTENNAS

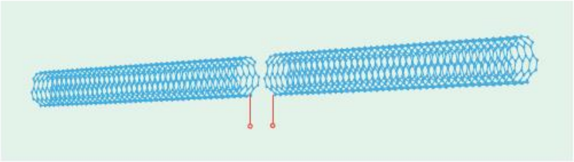
Ashika Zulfia – IV Year

CNTs facilitate an extreme miniaturization due to slow wave propagation effects [62]. CNTs exhibitexceptional electron transport properties, yielding ballistic carrier transport at room temperature with a mean free path of around 0.7 mm and a carrier mobility of 10,000 cm2/Vs. Due to the slow-wave propagation of electromagnetic waves in CNT structures, the wavelength of electromagnetic waves propagating in CNT structures is considerably smaller than the free-space wavelength. This effect occurs due to quantum transport effects in the CNT yielding a quantum capacitance and a kinetic inductance in addition to the geometric capacitance and inductance. CNTs exhibit a very high inductance per unit length due to the high kinetic energy of the electrons. The high inductance results in an electromagnetic slow-wave propagation along a CNT transmission line configuration with a phase velocity in the order of c0/100 to c0/50 [69], where c0 is the speed of light in free space. CNT nano antennas much shorter than the operating wavelength can be brought into resonance and potentially be used as radiation elements. A CNT nano antenna is usually an electrically extremely short antenna, that is, it is considerably shorter than the free-space wavelength. The appearance of slow waves makes CNT antennas interesting for wireless communication between circuits at the micro- and nano scale or between nano circuits and the macroscopic environment, [70]. Figure 20 shows a schematic drawing of a CNT dipole antenna. An analytic expression for the surface conductance of a single-walled CNT was given that can be incorporated into the integral equations to account for the specific electron transport properties. Copper and carbon dipole nano antennas are investigated using modified Hallén and Pocklington integral equations, which incorporate the CNT surface conductance. It was found that CNT dipoles start to go into resonance at much lower frequencies than initially assumed. This can be explained from the fact that electromagnetic waves are propagating along CNTs, forming surface plasmons, which have a reduced propagation velocity and, thus, have shorter wavelengths. So, CNT dipoles with several micrometers in length start to resonate in the low terahertz region, where the wavelengths are 50–100 times longer compared to the length of the CNT dipole. Due to the extremely high aspect ratio (length/cross sectional area), both metal nanowires as well as CNTs have ac resistances per unit length in the order of several kilo ohm per micrometer . This high resistance causes high-conduction losses and thus seriously decreases the efficiency and the achievable gain of nano antennas. The efficiency of a CNT dipole antenna is estimated to be in the range of –60 to –90 dB, which results from the high-conductance losses. The situation in the case of metal nano antennas is similar. Although low-power levels are sufficient in modern communication links, the inherent loss introduced by metallic or CNT nano antennas limits their applicability considerably. One approach to bypass the resistance problem could be the usage of arrays of nano antennas or a bundle of parallel nanowires. In this case, the resistance can be decreased to an acceptable value; however, the slow wave effect is lost. Therefore, by an appropriate choice of geometry and the number of nanowires, the properties of nano antenna structures have to be optimized.

CARBON NANOTUBE OVER METALLIC GROUND PLANE.



CARBON NANOTUBE DIPOLE ANTENNA



GRAPHENE ANTENNAS

M.Karthikeyan – IV Year

A promising alternative to CNT antennas could be planar structures such as two-dimensional (2-D) grapheme layers. Graphene is a 2-D material consisting of a monoatomic layer of carbon atoms ordered in a honeycomb structure, as depicted in Figure. It exhibits an excellent crystal quality and unique electronic properties. Morozov metal have shown that electron-phonon scattering in graphene is so weak that room temperature electron mobilities as high as 200,000 cm^2/Vs can be expected if extrinsic disorder is eliminated. Like CNTs, graphene also exhibits excellent conductivity and slow wave properties. The achievable slow-wave effect in plasmon modes is in the order of c0/100. At terahertz frequencies, a population inversion in the graphene layer can be realized by optical pumping or forward bias, which yields an amplification of the surface plasmon. Graphene allows the realization of planar structures and active circuits.

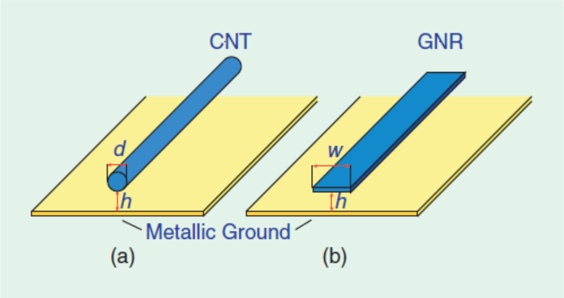


Figure shows patch antennas based on CNTs and graphene nanoribbons (GNRs).

Theoretical investigations have shown that antennas with sizes in the order of several hundred nanometers are suitable to radiate electromagnetic waves in the terahertz band, that is, 0.1–1 THz. Graphene has also been used as substrate for metallic antennas. Metallic dipole antennas and arrays of dipole antennas have been paterned on a graphene layer. The antennas have been operated at 120 GHz. Using the high-resistivity and low-resistivity state of the graphene, the antenna radiation patterns could be controlled.