A Review on opportunities and challenges of Nano Antenna for Terahertz Communications

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***Abstract* — Radiation and propagation of enhanced and coherent fields at Nano scale is possible by using Optical Nano-Antennas and Microwave Antennas. Infrared and visible radiation has great ability to enhance the light interaction with Nano scale matter when Nano antennas are at the sensing part due to their ability to efficiently link broadcasting and spatially confined optical fields. This ability unravels a massive potential for applications reaching from Nano scale optical spectroscopy and microscopy over integrated optical Nano circuitry, solar energy transformation, opto electronics and density of states engineering to ultra-sensing and enhancement of optical nonlinearities. Optical nano-antennas, nowadays offering researchers a broaden area of electromagnetic spectrum from lowest radio frequency to X-ray for its design, analyses and prediction of upcoming inventions. Their applications in areas with demanding necessities, i.e. in imaging, sensing, energy storage and cure and prevention of diseases has brought revolutionary progresses. This paper reviews and discusses about the importance of Terahertz applications in nanotechnology. In the present work, fabrication and characterization techniques in Nano antenna manufacturing are reviewed. The research taken with respect to the used materials, antenna structure and it's parameters along with its applications are compared.**

Keywords: Nano antenna; THz; lithography; milling; microscope; rectenna; spectroscopy; Plasmon.

I. INTRODUCTION

Optical Nano antennas (ONAs) are in the visible range of EM spectrum and equivalent of microwave and radio frequency (RF) antennas. There is a lot comparison between an optical Nano-antenna and RF antenna. In modern communication RF antennas are important devices with the sizes of the order of several centimeters to few centimeters. On the contrary, ONAs are in few hundred nanometers size, therefore it finds in numerous applicability in sub wavelength hotspots [1]. On account of the dimensional limits, fabrication capability and characterization conditions, these Nano antennas has several challenges. The present consideration from RF antennas to ONAs can be limited based on the issues of high losses in optic frequencies. Also, the novel process needs expansion of latest modelling competencies. In order to plan the optical conduct of deviations from RF antennas the said expansion is responsible [2].

II. NANO ANTENNA

A. Behavior of Nano-Antennas

In order to tune an antenna at derived frequency can be achieved by adjusting the Inductance L and Capacitance C to bring the resonance, so it is true from the perfect metals to plasmonic materials from RF to optical regime. The research and outcome is already pointed out by R. Feynman in 1959 by very small values of L and C [3]. This can be realized by decrease the dimensions of the antenna to the scale of the wavelength. And to achieve this when move is from higher frequencies and eventually reach up to IR and Visible light range, the metals are no longer perform as perfect conductors. The main dissimilarity between the interaction of low frequency and very high frequency EM waves is the conduction of electrons in metals branches from a finite effective mass of electrons. So due to increase in frequency such effective mass causes electrons to react with variation of phase lag to the sinusoidal electromagnetic field [4].

Therefore in perfect conductor material when operates at low frequencies Plasmon resonances are not seen, since those materials do not exhibits the phase lag between charge response and excitation of electron. This is how the existence of localized Plasmon resonance is observed and characterized for visible frequencies for optical application e.g. higher Ohmic losses compared to the RF range. Therefore at lower frequency doped semiconductor responds with its dominant metallic property and makes it potential use for the surface plasmon resonance at microwave, IR and for optical frequencies [5].

B. Nano Antennas - Optical Frequencies

Nowadays researchers have started taking much interest in antennas at optical frequencies. The EM waves at optical frequencies are being manipulated with considering most popular and advantageous standards such as mirrors and lenses. The wavelength of green spectral in visible light spectrum is of 500 nm, which corresponds to an energy of 2.5 eV. So the matter and photon interaction will be high enough due to high energy of photon with moving transitions of the electronic states of restricted electrons. Therefore optical antennas are able to make precise confinement of EM waves to very small lengths and also very well release radiation into far field with confined sources. Hence it provide the great chances to adapt the interaction of light

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with nano scale matter, which lifted the fundamental shortcomings to a large extent [6].

Therefore in the light wave communication i.e. nano scale matter interaction makes the prominent idea and fundamental concept behind optical nano-antenna. Nano antennas gives a potential applications in broad area due to their enhanced localized field while illumination at the feed point and its ability for localize fields e.g. the spacing between two feed points. Both confined field and enhancement initiate strong interest in related areas of ultra-sensing, optical effects, imaging as well opto-electronics and for solar energy transfer.

III. FABRICATION METHODS AND CHALLENGES

The exact geometry and dimensions acts as a prime need for the resonances of optical antennas, most reproducible and reliable structuring techniques requires for the fabrication of Nano antennas with approximate resolution below 10 nm for accuracy in critical dimensions, such as antenna length or size of feed gap. This cause the urgency of Nano structuring techniques for the realization of optical and plasmonic devices which is the main limitation and considered one of the main challenge.

Several top down and bottom up nano fabrication methodologies has been applied for experimental realization of optical antennas. There are two classifications of fabrication methods i.e. Electron-Beam Lithography (EBL) [7] and another one is Focused-Ion Beam (FIB) [8] milling..

A. *Electron Beam Lithography*

EBL is one of the most popular techniques used for fabrication of Nan antennas over a flat substrate. Usually in employment of EBL, the Polymethyl methacrylate (PMMA) which is a high resolution electron sensitive resist is used for patterning over substrate by means of an electron beam. The patterns are then established and selectively removed. However the patterning is done by an electron beam, the spatial resolution of the pattern is typically below 5 nm. Since, due to use of multicrystallinity of the deposited metal layer, the final structural resolution is generally not very good. [7].

B. *Focused Ion Beam Milling*

One more efficient machining technique used to realize the optical antennas is of FIB milling [8]. A liquid metal ion source extracted the accelerated ions for FIB structuring is done by the localized sputtering of the material. The emitted ions are accelerated and focused into a beam with a few nm spot and produces a desired pattern over a conductive substrate. The main advantages of FIB milling are the very good resolution and its broad applicability to almost any type of conductive material and allowing the gaps in the 10-20 nm range for the fabrication of prototype surface nanostructures [8].

C. *Nano Imprint Lithography*

Nano-Imprint Lithography (NIL) is much cheaper and has a high throughput alternative to both EBL and FIB patterning methods. The NIL process uses a hard mold which contains all the surface topographic structures to be shifted onto the sample and is pressed in controlled temperature and pressure into a thin polymer film which creates a thickness distinction, in opposed to the serial beam based lithography techniques by using ions, photons or electrons to define Nano patterns. [9, 10].

IV. CHARACTERIZATION TECHNIQUES

Material structure and its various properties can be measured by using Characterization technique to study material science in depth. It is a basic process in the field of material science, without which no scientific understanding of engineering materials could be determined. The scope of the term often varies as of some definitions limit the terms use to techniques which study the properties of materials and microscopic structure, while others use the term to refer to any materials analysis process including macroscopic techniques such as thermal analysis, mechanical testing and density calculation. Following is the classifications of characterization techniques.

- Optical Microscope
- Transmission Electron Microscope (TEM)
- Scanning Electron Microscope (SEM
- Scanning Tunnelling Microscope (STM)
- Scanning Probe microscope (SPM)
- Atomic Force Microscope (AFM)

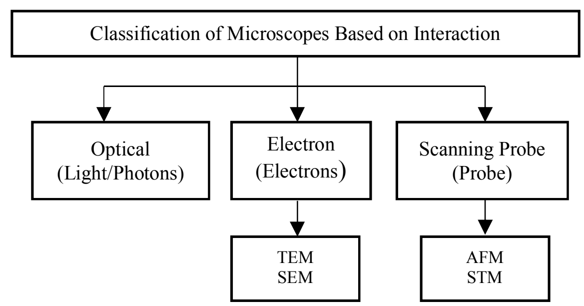

Fig.1 Classification of Microscopes [11-19]

The most common microscope (and the first to be invented) is the optical microscope, which uses light to pass through a sample to produce an image. There are many other types of microscopes, and they can be classified in different ways. Fig.1 shows the classification of microscopes based on Interaction.

V. LITERATURE SURVEY

A. *Literature Survey of Used Materials*

Nano antennas are designed with various properties of materials with the help of Nanostructured composition at the terahertz frequency from 0.1 THz to 10 THz. Researchers and scientists are taking more interest in terahertz frequency and its application areas due to the limitation when worked in microwave frequency range. Here the literature review has been started from the various property materials used, as a conducting or dielectric substrate requirements.

Anil Kumar [4] in 2011 in his dissertation demonstrated and invented the cheaper technique of patterning of metal nano structures which is having a features of up to sub- 10 nm of an electrochemical process. Along with this he also demonstrated the Cathodoluminescence imaging spectroscopy to be used to map the various modes of triangular and bowtie antennas by using Gold and Silver materials at 500-800 nm.

Kumud Ranjan Jha and G. Singh [5] in 2011 has analysed a Cavity type terahertz dipole antenna using the effective medium approach and ray tracing technique to predict the directivity of the antenna. The antenna is of rectangular strip with a ground plane flat square copper conductor is used in the frequency range of 600-620 GHz. To corroborate the proposed analysis, the operating frequency of the antenna has been scaled down by a factor of 20 in the millimetre wavelength range.

Kumud Ranjan Jha and G. Singh [6, 7] in 2011 and 2012 has analysed and simulated a patch Yagi-Uda type printed array antenna at 590 GHz. He used low dielectric permittivity photonic crystal substrate material with periodically drilled air cylinders while keeping the substrate thickness equal to 200 μm. He undergone parametric optimization to enhance the gain of the proposed antenna.

Josep Miquel Jornet and Ian F. Akyildiz [13] in 2013 proposed, rectenna and analysed a novel Graphene based Nano antenna, which exploits the behaviour of SPP waves in semi finite size Graphene Nano ribbons at 150 THz. He also investigated these Nano-antennas are able to operate at much lower frequencies than their metallic counterparts, e.g., the terahertz band for a 1 μm-long and 10 nm-wide antenna.

Mehta and M. E. Zaghloul [14] in 2014 proposed and determined that placing monolayer and bilayers of Graphene sheets on top of the optical nano antenna will result in a change of resonating wavelength. And Luke Zakrajsek, Erik Einarsson [17] in 2016

Mario Barei and Peter M. Krenz [9] in 2013 demonstrated first time the fabrication of a rectenna array using an efficient parallel transfer printing process featuring nearly one million elements. During his investigations of Titanium and Gold materials, he found that the dielectric permittivity is strongly dependent on the dielectric thickness. So he chooses Titanium-Titanium Oxide-Gold as the optimum material combination for obtaining nonlinear MIM diode properties. Similarly Evgeny G. Mironov and Ziyuan Li [12] in 2013 examined that an increase in the power density capacity of the Nano-antennas can be achieved by replacing Gold with Titanium.

M. N. Gadalla and M. Abdel-Rahman [10] in 2014 demonstrated a resonant bowtie THz antenna with a rectifier of Gold material for harvesting Infrared energy. Nopparat Thammawongsa and Somsak Mitatha [11] in 2013 proposed an embedded Nano-antenna system using the optical spins generated from a particular configuration of microrings at 1.55 μm. While in this case the suitable thermal distribution of a Gold Nano antenna is proposed. N.A. Eltresy and H.A. Malhat [19] in 2016 respectively proposed and optimized a thin dipole made of Gold and printed on a Silicon dioxide substrate at 28.3 THz. A metal insulator metal (MIM) diode is integrated with the Nano antenna dipole to rectify the received energy.

Mohamed Hussein and Nihal Fayez [15] in 2014 has experimented new design of antenna consists of three element Nano antenna with elliptical shape from 400-1400 nm. During his investigation he concluded an attempt to find metal that is more abundant and less expensive, the metals with high electrical conductivity such as Gold and Silver are preferred for the designing at nano scale.

B. Literature Survey with Fabrication Methods

Nano antenna fabrication carried out since last 5 years. The preferred techniques by various researchers are Electron beam Lithography & Solid state Superionic Stamping by Anil Kumar [4] in his final dissertation. As well the same EBL has completed successfully with Atomic layer deposition and Sputtering methods by M. N. Gadalla and M. Abdel-Rahman [10].There he designed bowtie Infrared Rectenna for Infrared energy harvesting application. B. Mehta, M. E. Zaghloul [14] by using Graphene material with same Electron beam Lithography but using Metal deposition and lift-off process for fabrication of Nano antenna. It is been used for the sensors in the Biological & Chemical gas areas.

Seeing various fabrication methods, but having some advantageous over Electron beam Lithography, Luke Zakrajsek and Erik Einarsson [17] developed the Nano antenna for the Graphene material by using Focused Ion Beam lithography with Chemical vapor Deposition (CVD) technique.

Parallel transfer printing process fabrication technique is done for Nano antenna with MIM diode for Titanium and Gold material [9]. The application covered by this is IR detectors and solar energy harvesting.

C. Literature Survey with Characterization Techniques

Scanning Electron Microscope (SEM) produces images by detecting secondary electrons which are emitted from the surface due to excitation by the primary electron beam. In the SEM, we use much lower accelerating voltages to prevent beam penetration into the sample since what we require is generation of the secondary electrons from the true surface structure of a sample. Due to seen this advantageous of SEM over another Microscopy techniques it is been observed during literature survey that it is profoundly been used by many researchers for studying the characterization of nanostructured Nano antenna [5, 9, 10, 12, 14].

TABLE. 1 Comparative of Nano Antenna with Materials, fabrication, characterization methods and applications [3-23]

Sr. No.	Author, Publication & Year	Material Used	Frequency / Wavelength	Software Used	Fabricated By	Characterization Technique	Antenna Structure	Advantages	Applications
1.	Kumud Ranjan Jha, G. Singh, Optics Communications, Elsevier, 2011 [5]	Copper	610 GHz (THz/ mm wave)	CST & HFSS	----	----	Fabry-Perot Cavity Type Antenna	----	Surveillance, Imaging and Sensing
2.	Kumud Ranjan Jha, G. Singh, Infrared Physics & Technology, Elsevier, 2011 [6]	Photonic crystal substrate	610 GHz (THz/ mm wave)	CST & HFSS	----	----	Yagi-Uda structure	Gain Improvement	----
3.	Anil Kumar, Dissertation Thesis, University of Illinois at Urbana-Champaign, 2011 [3]	Gold and Silver	500-800 nm	FDTD	Electron beam Lithography & Solid state Superionic Stamping	SEM based Cathodoluminescence Imaging spectroscopy	Bow Tie, Triangular in shape	----	----
4.	Kumud Ranjan Jha , G. Singh, Springer Science Business Media LLC 2012 [7]	Photonic Band gap Material	600 GHz (THz/ mm wave)	CST & HFSS	----	----	----	Directivity and Gain Improvement	----
5.	Josep Miquel Jornet and Ian F. Akyildiz, IEEE journal on selected areas in communications/supplement part 2, December 2013 [13]	Graphene	150 THz	Analytically and Numerically computed	----	----	Plasmonic Nano-patch	SPP wave	Biomedical, Industrial, Environmental
6.	Mario Barei, IEEE trans.Nanotechnology, 2013 [9]	Titanium and Gold	28THz	----	Parallel transfer Printing process	Scanning Electron Microscopy	Antenna with MIM diode	----	IR detectors and Solar energy harvesting
7.	Nopparat Thammawongsa, Somsak Mitatha, IEEE Transactions On Nano bioscience, Vol. 12, No. 3, September 2013 [11]	Gold	1.55 µm	----	----	----	PANDA ring resonator	Optical spin Concept	Diagnostic of many physical ailments
8.	Evgeny G. Mironov, Ziyuan Li, Haroldo T. Hattori, IEEE access, journal of light wave technology, vol. 31, no. 15, august 1, 2013 [12]	Titanium	----	FDTD	----	Scanning Electron Microscopy	----	Power density capacity of Ti is more than Gold	Nano imaging, Nano-particle detection
9.	Mohamed Hussein, Nihal Fayez Fahmy Areed, IET Optoelectronics 9th February 2014 [15]	Gold and Silver	400-1400 nm	FDTD & MOM	----	----	Flower shaped Dipole	Large BW, Harvesting efficiency 32.7%	Solar energy harvesting

TABLE. 1 (Continued

Sr. No.	Author, Publication & Year	Material Used	Frequency / Wavelength	Software Used	Fabricated By	Characterization Technique	Antenna Structure	Advantages	Applications
10.	M. N. Gadalla, M. Abdel-Rahman, Nature, Scientific Reports,2014 [10]	Gold	28.5 THz	HFSS & COMSOL	Electron beam Lithography (30Kv & 11Pa),Atomic layer deposition, Sputtering	Scanning Electron Microscopy	Bow-tie ,IR Rectenna (Nano antenna+ Diode)	----	Harvesting IR energy
11.	B. Mehta, M. E. Zaghloul, IEEE Photonic Journal, Volume 6, February 2014 [14]	Graphene	----	FDTD	Electron beam Lithography ,Metal deposition and lift-off process	Scanning Electron Microscopy CCS 175- Spectrometer	----	Good absorption for different molecules	Biological & Chemical gas sensors
12.	Giuseppe Piro, Ke Yang, Gennaro Boggia, IEEE Transactions On Nanotechnology, Vol. 14, No. 3, May 2015 [16]	----	----	----	----	----	----	Channel capacity and transmission ranges included	Wireless communication in human tissues ,Medical and Internet of Nano-things (IoNT)
13.	Rohit D. Apurva, Neha V Thigale, IEEE Access, 2016 [20]	Copper	30 THz	HFSS	----	----	Array of Nano-patch	Utilization of spectrum of solar energy	Solar energy harvesting
14.	Fatemeh Taghian, Vahid Ahmadi, Journal of light wave technology, vol. 34, no. 4, IEEE ,February 15, 2016 [21]	Indium Tin Oxide (ITO)	400-1000 nm	FDTD	----	----		SPP wave	Solar energy harvesting
15.	N.A. Eltresy, H.A. Malhat, National radio science conference, Aswan, Egypt (NRSC 2016), Feb 22□25, 2016 [19]	Gold	28.3 THz	CST & HFSS	----	----	Rhombic Antenna with MIM diode	Dual polarization	Solar energy harvesting
16.	Waleed Tariq Sethi, Hamsakutty Vettikalladi, Micro & Nano Letters, Vol. 11, Iss. 11, pp. 779–782, 2016 [18]	----	1550 nm	CST & HFSS	----	----	Tunable plasmonic equilateral triangular dielectric resonator Nantenna	High Directivity and BW- 2.58%	----
17.	Luke Zakrajsek, Erik Einarsson, IEEE antennas and wireless propagation letters, vol. 15, 2016 [17]	Graphene	500 nm	COMSOL Multiphysics	Focused Ion Beam lithography with Chemical vapor deposition (CVD)	----	----	SPP Wave	----
18.	Mona Nafari, Josep Miquel Jornet, IEEE, MAY 2017 [23]	----	----	COMSOL Multiphysics	----	----	Metallic Nano-dipole	NA as a Tx and as a Rx with SPP Wave	Performance of Plasmonic NA in reception and transmission

VI. CONCLUSION

This paper discusses various aspects related to the study and implementation of optical Nano antennas. Because of their Nano scale size, its fabrication and characterization offer significant challenges. Therefore, a thorough study of nano patterning of material with the fabrication, characterization and applications of nano antenna has been consider. This includes Nano scale quantum optics, lithography, microscopy, spectroscopy, sensing, photovoltaic, trapping, and many others. The development of advanced Nano scale machines is possible into single entity by an integration of several nano devices. By means of communication, Nano machines will be able to synchronize with each other and perform more complex tasks in a distributed manner. The opportunities and challenges are reviewed for the fast growing field of nanotechnology and will offer its services to the next generation of optical imaging, optical sensing, Nano optics, and in Nano energy harvesting applications.

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