Design and Optimization of a Four-Arm Metamaterial Reflector for High Reflectivity

A DISSERTATION

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FOR THE AWARD OF THE DEGREE
OF

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IN
PHYSICS

Submitted by:

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MAY, 2023

CANDIDATE'S DECLARATION

We hereby certify that the work, which is presented in Dissertation-II entitled "**Design and Optimization of a Four-Arm Metamaterial Reflector for High Reflectivity**" fulfillment the requirement for the award of the Degree of Master in Science in Physics and submitted to the Department of Applied Physics, Delhi Technological University, Delhi is an authentic record of our own, carried out during a period from January to May 2023, under the supervision of **Dr. Yogita Kalra** and **Dr. Kamal Kishor.**

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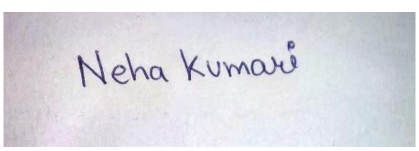

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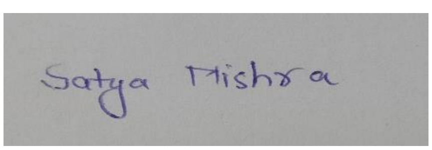

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Date: 31st, May 2023 **Neha Kumari (2K21/MSCPHY/33)**

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ABSTRACT

We are examining a four-arm metamaterial reflector whose frequencies are ranging between 1 to 25 GHz. As the name suggests, this reflector is a four-arm structure built up of copper arms and a FR4 substrate. This design is further intensified using COMSOL in order to achieve excellent frequency and minimal loss over the given frequency range. Thus, the results of this suggested reflector show a high level of reflection which is 88.97%. Some of common applications of this suggested reflector are Antennas, Radar Systems and Wireless communication equipment's. In a nut shell, this reflector offers a simple and efficient method for obtaining high reflectivity and low loss in a compact and lightweight container. Also, the suggested design is a promising choice for further research and development in the field of metamaterials.

CHAPTER 1

INTRODUCTION

In 1999, Rodger Walser of the University of Texas in Austin coined term "metamaterial," which was initially described as “Macroscopic composites with a synthetic, three- dimensional, periodic cellular architecture that aim to provide an optimal blend of two or more responses to a given excitation that is not present in nature”. The metamaterial is described as "a substance that obtains its properties from its structure rather than directly from its composition”. Not all metamaterials fit the definitions given above, but some do. Metamaterials certainly shows the latest achievements in research in the field of ordinary materials and complex media. The name refers to a class of man-made materials that demonstrate surprising and unusual property of electromagnetic are not present in nature. It was a suggestion made in the scientific community seeking to identify the substance in complicated media Following this definition, and in accordance with the prevailing potential of this community, the Greek word ``meta" has been used to mean the ``emergence" of new characteristics from a specific combination. In actuality, whether it has a periodic or non- periodic structure, metamaterial is a macroscopic composite with a purpose is determined by both the chemical makeup and the cellular design. If a metamaterial is thought of an operative medium, then the cellular size must also be less than or equal to the sub-wavelength as an extra condition.

Fig: -1.1 A Periodic metamaterial structures.[1]

The subordination of metamaterial properties on the cellular design offers a lot of controllability over metamaterials(1). Through the use of metamaterial structures, new materials that are not found in nature can be able to produce this is the major benefit of metamaterials. A chemical components and linkages present in a bulk material primarily control its properties. People have never stopped trying to study and manage material properties properly. For instance, our predecessors were able to create alloys more than three thousand years ago in order to enhance the mechanical properties of metals. A basic platform for the entire industry of semiconductor, which was founded in 1960, was laid by the silicon conductivity, which will be made in various numbers of magnitude greater by some doping. A goal of modern nanoscience and nanotechnology is to research that materials which have electronic, optic, thermic and other mechanical properties beginning at the atomic or molecular level. Considering all initiatives, they are greatly increased the variety of materials that are available to consumers. Over the past ten years, metamaterials have provided acompletely new way to improve people's ability to freely design material properties. In contrast to the aforementioned instances, metamaterials' physical characteristics are mostly influenced by their internal, unique structures rather than the intrinsic features of their chemical constituents. In conventional materials, these artificial structures perform the same roles as atoms and molecules. However, by carefully controlling their electromagnetic waves (EM) interactions, it is observed that these are able to provide interesting different physical property that are not present in naturally found materials and chemically synthesized material. Because of the various different combined constructions these arereferred to as metamaterials, which literally refers to materials that go beyond those found in nature(2).The figure below shows that the basic structure of metamaterial design.

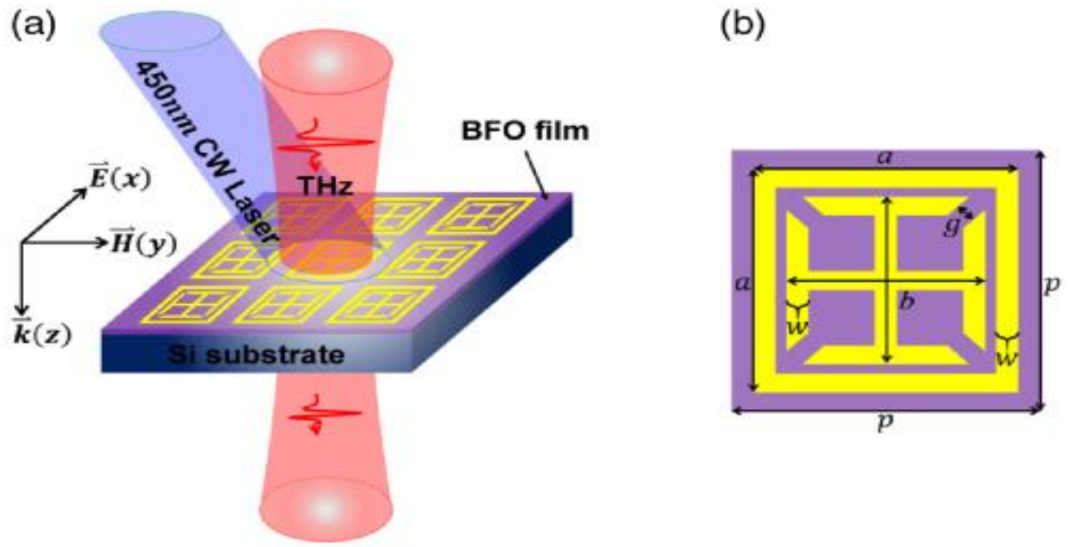

Fig:- 1.2 Metamaterial unit cell Structure with Substrate.

CHAPTER 2

CLASSIFICATION OF METAMATERIAL

The characteristics of the material properties determine that a system reacts to an electromagnetic field. The macroscopic parameters of these materials' permittivity [5]and permeability are used to describe these properties. By considering permittivity ε and permeability μ of the various classes of metamaterials, the different classification can be described by the graphical diagram as shown in figure.

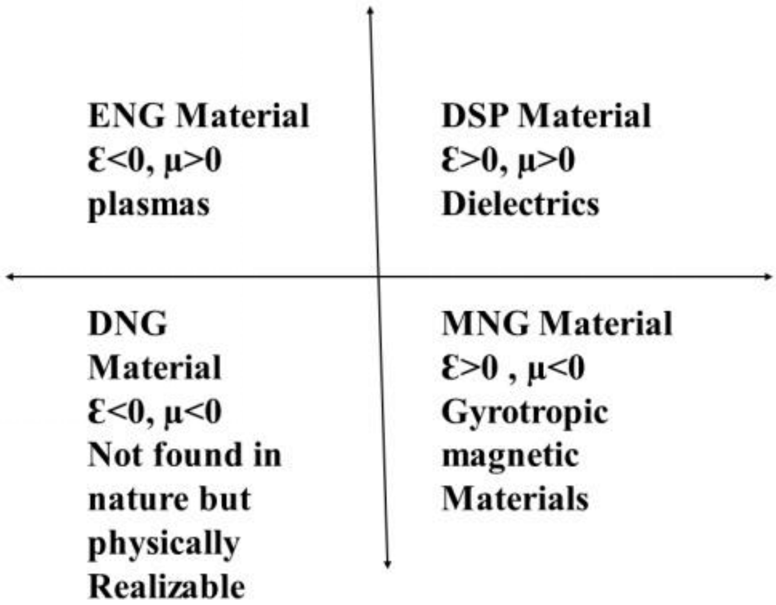

Fig:-2.1 Classification of Metamaterial

A medium is referred to as a (DPS) that is double positive media where both the permittivity and permeability are more than zero ($\varepsilon > 0$, $\mu > 0$). This description applies to the majority of naturally occurring media, such as dielectrics(3).A media whose permittivity is lower than zero whereas permeability is more than zero ($\varepsilon < 0$, $\mu > 0$) is known as (ENG) that is Epsilon negative medium. A particular frequency regime in verities of plasma exhibit these properties negative (MNG) media are defined as having a permittivity larger than zero and a permeability lower than zero ($\varepsilon > 0$, $\mu < 0$). This property is found in some gyro tropic materials in particular frequency regimes. Double negative (DNG) mediums are those whose permittivity as well as permeability values that are both less than zero ($\varepsilon < 0$, $\mu < 0$). Only artificial creations have been used todemonstrate this class of materials.

The two primary electromagnetism (EM) parameters that define a medium's EM property are electric permittivity (e) as well as magnetic permeability (m). Permittivity (permeability), which are based on the material's capacity to see the polarize responses to the electric(magnetic) fields, explains the physical interactions between an electric (magnetic) field anda medium. To represent all materials in terms of their EM properties, we employ the "material parameter space" depicted in Fig. The majority of dielectric materials fall under Region I in the upper right quadrant. This region is made up of materials which will haveboth positive permittivity and permeability. In a second quadrant, material such as metals, ferroelectrics, doping semiconductors may have negative permittivity at different frequency which is less than the frequency of plasma. Although some of the ferrite materials in Region IV have negative permeability, their magnetic responses quickly disappear above microwave frequencies. Quadrant III, where permittivity as well as permeability are simultaneously negatives, is a most intriguing area in the material parameter space.

Various metamaterials

The different types of metamaterials are described as follow

2.1 Electromagnetic Metamaterial

In the electromagnetism and physics particularly in the photonics and optic, metamaterial has emerged as a brand-new topic. They are utilized for microwave and optical applications, including novel kinds of antenna randoms, modulators, band-pass filters, lenses, and beam steerers. Structures are part of metamaterials. By possessing structural elements that areless than the electromagnetic radiation wavelength that interacts with different metamaterial which will influence those waves.

2.2 Negative Refractive Index

Since no natural found substance has a negative refractive index, creating such a structure is the biggest potential application of metamaterials. Glass and water are just two examples of the nearly all materials used in optics that exhibit positive parameters for both permittivity and permeability. Several metals at visible wavelengths are negative, including silver and gold. An object is opaque to electromagnetic radiation if it has either (but not both) of the negative charges. Although the parameters and fully describe the optical characteristics of a clear material, refractive index n is typically utilized. A refraction containing left-handed metamaterials as well as ordinary materials is shown in Fig.

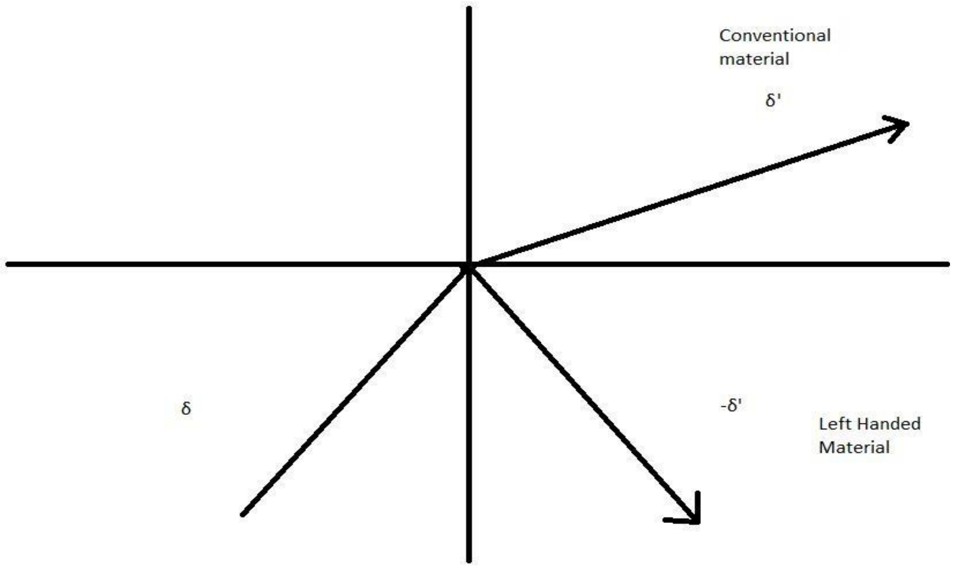

Fig:- 2.2 Demonstration of Ray Diagram of Metamaterial.

Positive ε and μ and are present in all known non-metamaterial transparent materials. By norm, n is calculated using the positive square root. Certain designed metamaterials have ε <0 and μ < 0 respectively. N is real because the product is positive. In such cases, it is important to calculate n's negative square root. Victor Veselago, a physicist, demonstratedthat certain materials can transmit light.

2.3 Different Classification of Electromagnetic Metamaterial

Double Negative Metamaterial (DNG)

In double negative metamaterials (DNG), the index of refraction is negative because and permeability permittivity both are found negative. Additionally known as Negative index metamaterials. The terms "lefthanded media," "media with a [13] negative refractive index," and “backward-wave media" are also used to describe double negative metamaterials DNGs.

Single Negative Metamaterial

Either permittivity and permeability not both are negatively correlated in single negative (SNG) metamaterials. These are the ENG and MNG metamaterials that are mentioned below. Two SNG layers have been combined into one meta-material in several interesting experiments. By doing this, another type of DNG metamaterial is effectively created. In orderto conduct wave reflection studies, a full slab of ENG and a MNG material have been bonded. As a result, characteristics like resonances, anomalous tunnelling, transparency, and zero reflection were demonstrated. Similar to DNG metamaterials, SNGs are inherently dispersive, therefore changes in frequency will affect their permittivity, permeability, and refraction index.

Electromagnetic Bandgap Metamaterials

A propagating light is controlled by electromagnetic bandgap metamaterials. A photonic crystal (PC), a form of metamaterial, or left-handed materials, a different class, are used todo this (LHM) Both belong to a new class of intentionally created structures, and they both regulate and affect how electromagnetic waves propagate (light)**.**

Double Positive Medium

Nature does contain a double positive media (DPS), such as naturally occurring dielectrics. Wave propagation is forward, permittivity and magnetic permeability are both positive.

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Bi isotropic and Bi anisotropic Metamaterial

The standard practice of classifying metamaterials as double, single, double positive are based at the presumption of metamaterial that is exhibits independent electric as well as magnetic response denoted through the parameter and in many cases of electromagnetic metamaterial, magnetic field produces an electrical polarization, which is known as magnetoelectric coupling, and the electric field creates a magnetic polarization. These mediums are referred to be bi-isotropic. A Bi anisotropic media which have magneto electric coupling are also called anisotropic.

Chiral Metamaterials

A metamaterial is known as chiral metamaterial when it was built from chiral components.

Slip Ring Resonators

The metamaterial having negative index (NIM), often referred to double negative metamaterial, having a split-ring resonator (SRR) as a part of component (DNG). They are also constituents of different kinds of metamaterial, like Single Negative metamaterial (SNG).SRRs are also employed in the study of metamaterial antennas, terahertz metamaterial, acoustic metamaterials dielectrics. Wave propagation is forward, permittivity and magnetic permeability are both positive.

Terahertz Metamaterials

Interacting metamaterials called terahertz metamaterials during terahertz frequencies. To further investigate or utilize the for materials like materials and metamaterials, typically a different frequency values is found as 0.1 to 10 THz. It relates with the wavelengths from 3 and 10 mm (EHF band) and 0.03 mm long wavelength edge of far infrared light.

Photonic Metamaterial

The subwavelength, periodic structure created artificially and intended to interact with opticalfrequencies called as a photonic metamaterial. The photonic metamaterial can be distinguished by structures of photonic band gap through its sub wavelength period.

Tunable Metamaterial

The metamaterials that can be adjusted at will in terms of frequency changes in the refractive index is said to be tunable.

Frequency Selective Surface (FSS) based Metamaterials

The fixed frequency metamaterial has been replaced by FSS-based metamaterials.

Nonlinear Metamaterials

It is also possible to create metamaterials that contain nonlinear media, or substances whose characteristics vary depending on the strength of the incident wave[17]. For nonlinear optics, nonlinear media are necessary.

Metamaterial Absorber

In order to produce a high electromagnetic absorber that metamaterial absorber will enhance the loss part of intricate effective values of parameters and permittivity and magnetic permeability. Since the creation by metamaterials with negative permittivity and permeability,the basic square shape of the metamaterial structure unit has given way to other shapes like as U, S, O, and fishnet, among others. In addition, the structure unit's size has changed from millimeter-scale dimensions to micro- and nano-scale dimensions. The terahertz, infrared, and visible frequency ranges were included in the applied frequency range of metamaterial.

CHAPTER 3

APPLICATIONS

3.1 Invisibility cloaking

The basic for trying to form a workable cloaking device is metamaterials. Beams of microwave are refracted by the cloaking device and they will pass near a "hidden" object inside by minimum distortions, giving the impression that nothing is there at all. Such a gadget typically includes enclosing the target object in a shell that interferes with light near it.

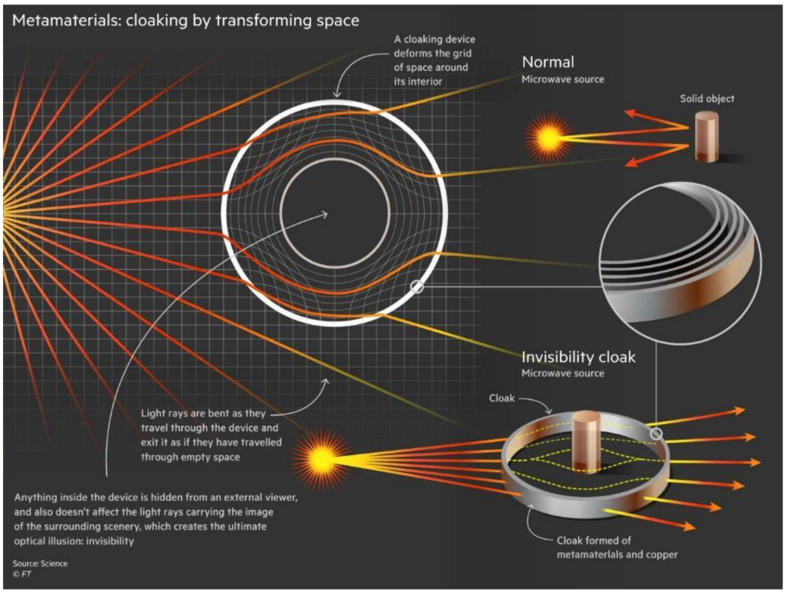

Fig:- 3.1 Invisibility Cloaking

3.2 Antennas

A couple of antennas known as metamaterial antennas employ metamaterials to enhance the system's performance. A radiated power of an antenna could be increased by the metamaterials. Negative magnetic permeability-achievable materials may be able to provide characteristics like electrical small size of antenna, strong directivity, variable operational value of frequency, exhibiting the array system. Additionally, antennas depend on metamaterials will show bandwidth performance increased efficiency. Metamaterials having synthetic materials with characteristics doesn't found in the natural world. The class of metamaterials with negative value of electric permittivity (ENG) and the value of Negative magnetic permeability (MNG), or both (ENG/MNG) is expected to significantly enhance antenna performance. Metamaterial which are based on antennas will include the revolutionary potential to break through the constrictive efficiency of the bandwidth constraint of natural occurring and traditional built electrically small antennas. The developed successfully, metamaterial antenna will enable some of the antenna elements to consider a larger frequency value, becoming useful for large efficient use of space in few areas or in small places Multiple input and multiple output (MIMO) antenna array benefit through the enhanced isolation between radio frequency or microwave channels thanks to usage of metamaterials surrounding antennas in the ground place.[18]. By utilizing forward and backward waves characteristics in antennas of leaky wave, metamaterials are found to employed to enhance the beam scanning values. To provide support at the surveillance sensor, navigation system, communication linkages, and command as well as control systems, a different metamaterial antenna system can be used.

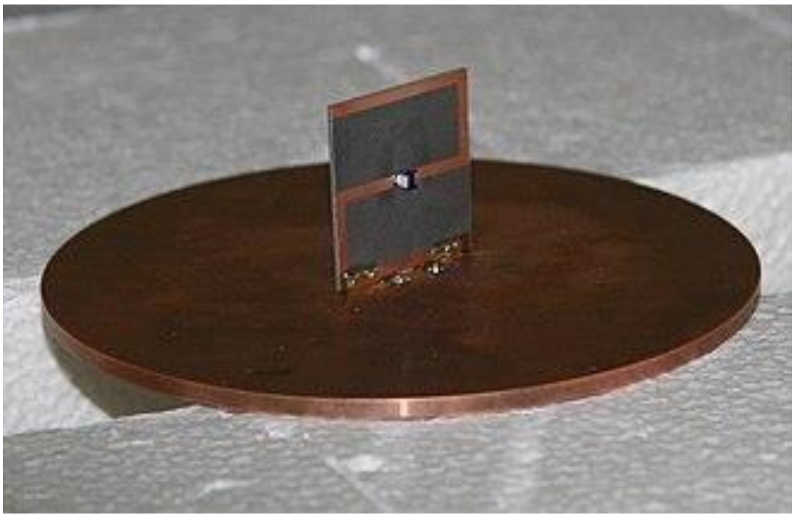

Fig:-3.2 Model of Antenna

3.3 Super lenses (Metamaterial lenses)

In order to attain resolution beyond the diffraction limit, a super lens incorporates metamaterials. Inherent in typical optical devices or lenses is the diffraction limit. In the absence of any aberrations, the best optical lens-based imaging systems are purely diffraction-limited. It's long been speculated that physics may be tweaked to increase resolution beyond the limits imposed by the airy disc diameter. Negative refractive index materials were regarded to be a viable option. This is why metamaterials have been proposed for use in the "super lens. “A super lens is a lens that goes above the diffraction limit by using metamaterials. The diffraction limit is a property of traditional lenses and microscopes that restricts their resolution fineness.

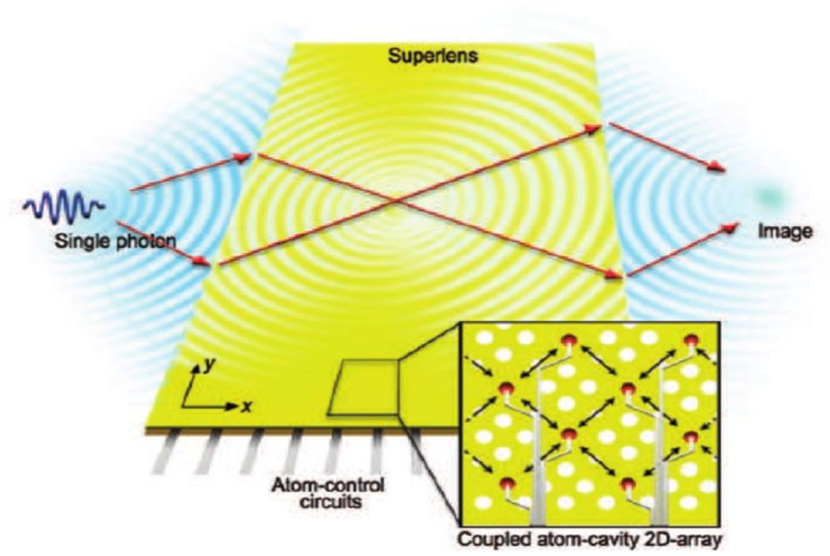

Fig :-3.3 Model of Super lens.

3.4 Acoustic Metamaterials

Acoustic metamaterials are materials that have been purposely created and are intended to regulate, direct, or alter sound in these different waveforms.

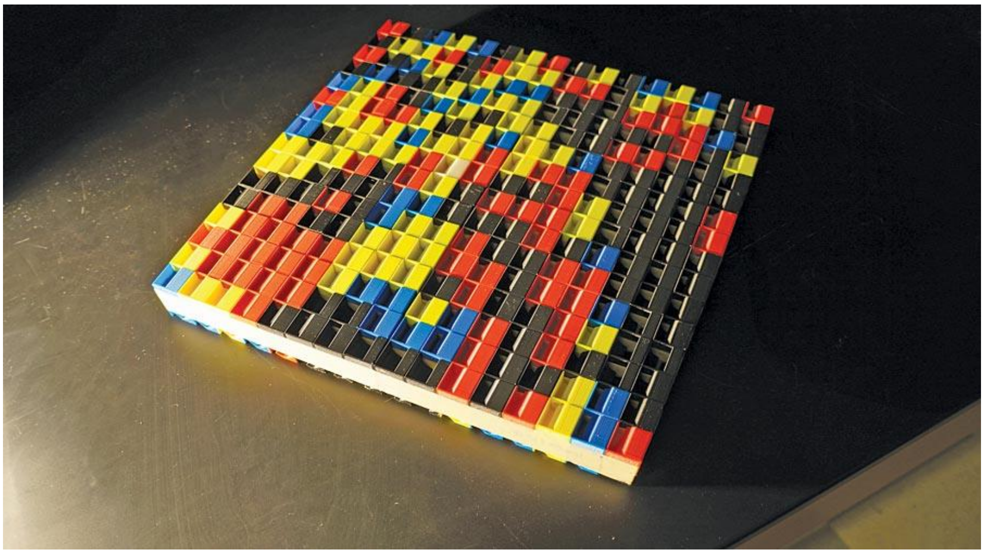

Fig:- 3.4 Acoustic Metamaterial

CHAPTER 4

DESIGN OF METAMATERIAL

Metamaterial design plays an important role in achieving the desired properties. To design a metamaterial, we take the dimension of metamaterial to be much smaller than the wavelength. This property makes metamaterial structure a special structure(4). Proposed metamaterial will be finalized through step-by-step design and observing the response of different properties to different design configurations. The suggested metamaterial is composed of copper material having thickness 0.2mm and conductivity (r) 5.80 x 10^7 S/m. FR-4 is a class of printed circuit board base material made from a flame-retardant epoxy resin and glass fabric composite. The FR-4 epoxy resin (circuit board) fiber is chosen as substrate material with dimension 3x3 mm having thickness of 0.2mm. Initially on the substrate, first we designed 4 blocks on the corner with length 1.3mm respectively with gap 0.1 mm .A straight rectangle box is drawn of length 2.2 mm and width 0.1 mm upper and bottom of the substrate and another t shaped rectangle block is drawn of length 1.8 mm and 0.5mm with width 0.2 mm on both the sides then a U shaped block is drawn 1st layer length 1.2 mm and width 0.6mm both the sides and 2nd layer length 0.8 mm and width 0.4 mm both the sides and the gap between these two layer is 2 mm. Similarly, another U shaped block is drawn upside down. Now the whole design is extruded to 0.2 mm.

This whole designed is set at the distance of 1.5 mm in a box of 3X3X3 Height, Width and Depth.

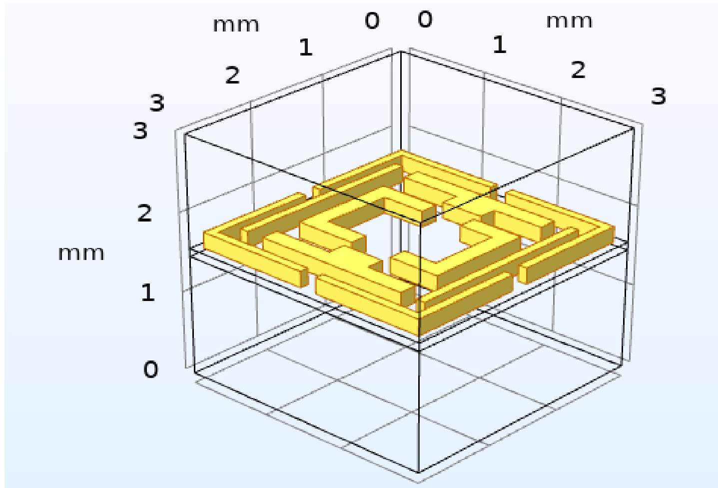

Fig:- 4.1 Front view with copper material.

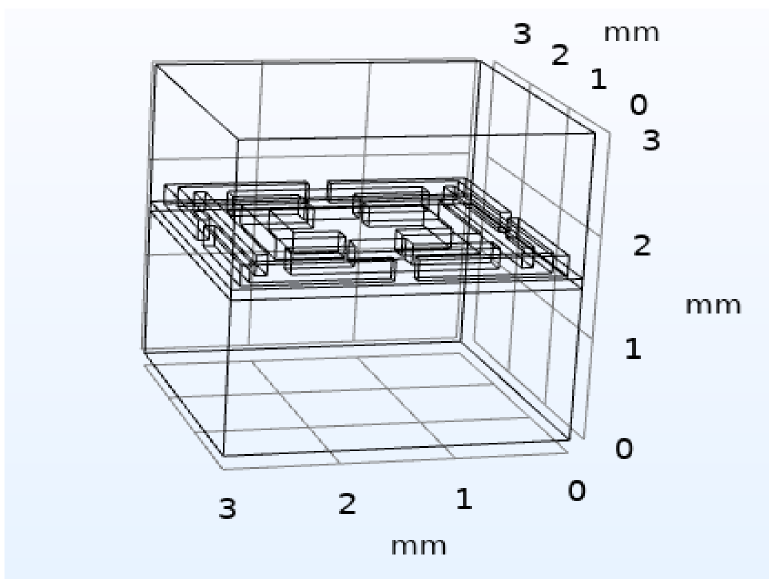

Fig:- 4.2 Front view of Design.

This design has 4 segments means the box is divided into 4 parts 1st part and 3rd part's material consist of air the 2nd part i.e substrate we selected FR-4 and 4th part is the design of unit cell in that segment we have selected copper material for this design.

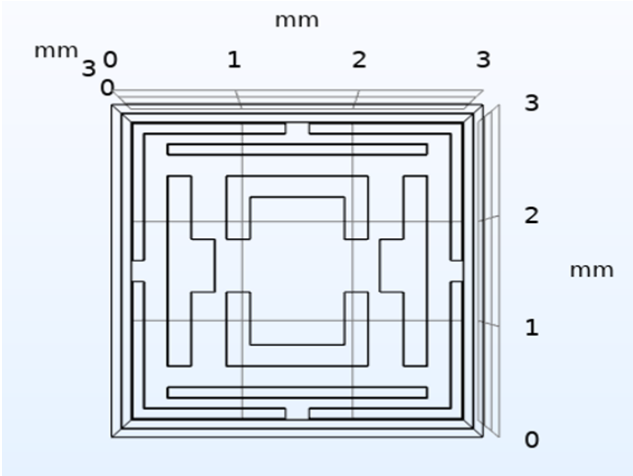

Fig:- 4.3 X-Y Plane view.

Material	Selection
Copper (mat1)	Domain 4-13
FR-4 (Circuit Board) (mat2)	Domain 2
Air (mat3)	Domain 1,3

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Estimation of the electromagnetic parameters and the S-Parameter:

In the characteristic impedance of the scattering parameter used to evaluate it in the RF module's finite element method using COMSOL Multiphysics simulation software(5). With the electric field polarized along the y-axis, the Perfect Magnetic Conductor and Perfect Electric Conductor boundary conditions are applied along the y- and x-axes, respectively. Along the z-axis, the electromagnetic plane wave moves. The Nicolson-Ross-Weir method is used to determine the proposed structure's permittivity (Ɛ), permeability (µ), and refractive index (n) effective medium qualities.

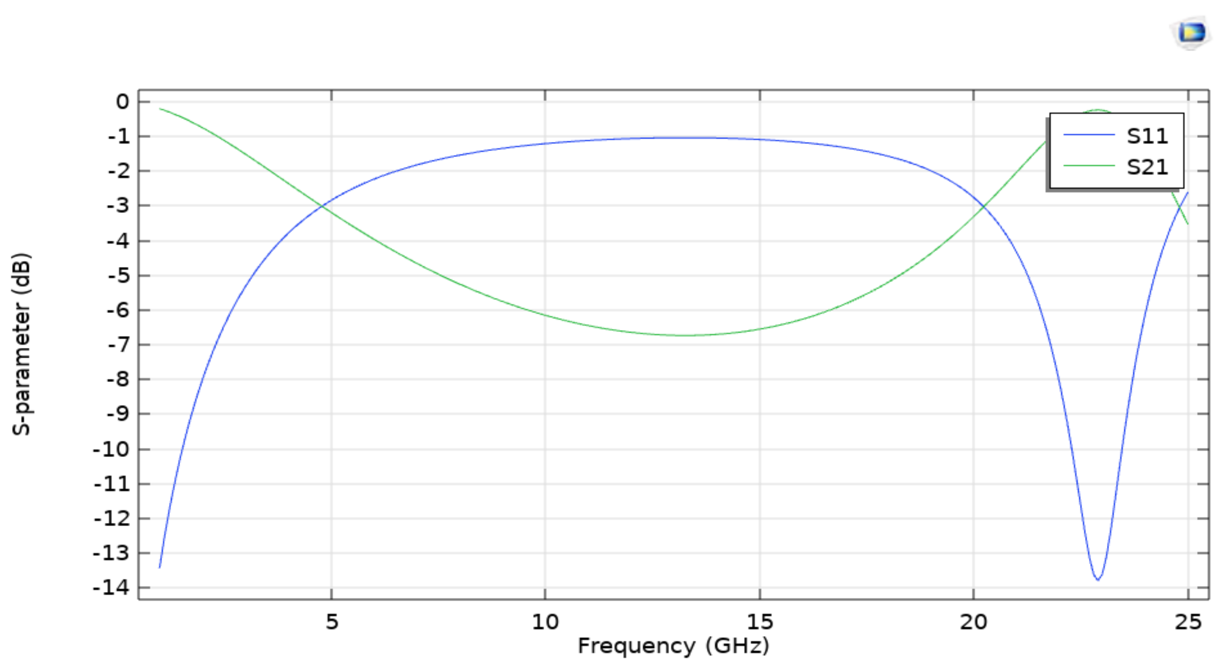

Fig:-5.1 S-parameter vs Frequency.

The suggested metamaterial unit cell's transmission coefficient (S_{21}) and reflection coefficient (S_{11}) are shown in Fig 1

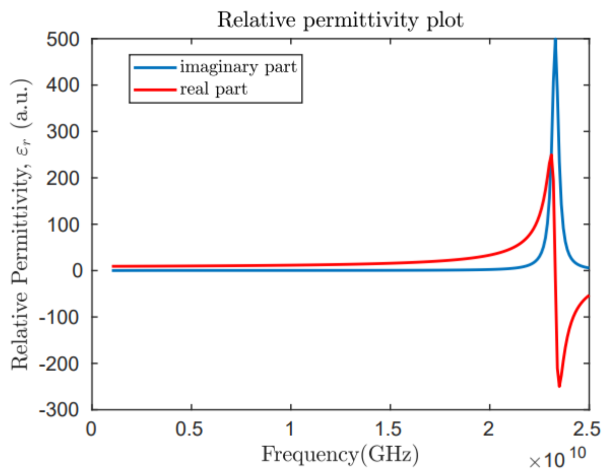

Fig:-5.2 Relative permittivity vs Frequency (GHz)

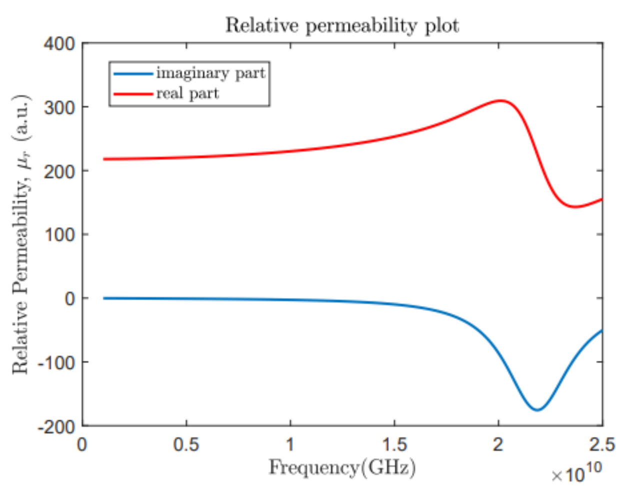

Fig:- 5.3 Relative permeability vs Frequency (GHz)

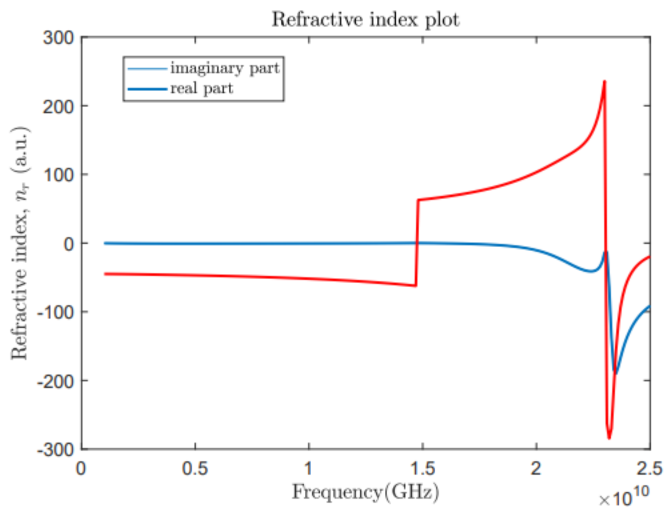

Fig:-5.4 Refractive index vs Frequency (GHz)

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The transmission coefficient (S_{21}) shows a dip at resonance frequencies 12.50 GHz with the amplitudes of -7 dB, similarly reflection coefficient (S_{11}) showed resonant frequency(6) with amplitude of -1dB at frequencies of 14GHz. Figure shows a plot of the proposed metamaterial's refractive index, permittivity, and permeability. In Fig. 1, the peak frequencies at 24GHz, shows negative permittivity with amplitude -250 and for permeability there is slight dip on frequency for 22GHz as shown in Fig with amplitude 300. negative refractive index is displayed on frequencies 23.80GHz and 15GHzwith amplitude -275and -55as shown in figure.

5.2 Electric field distribution: Distribution of electric field is shown

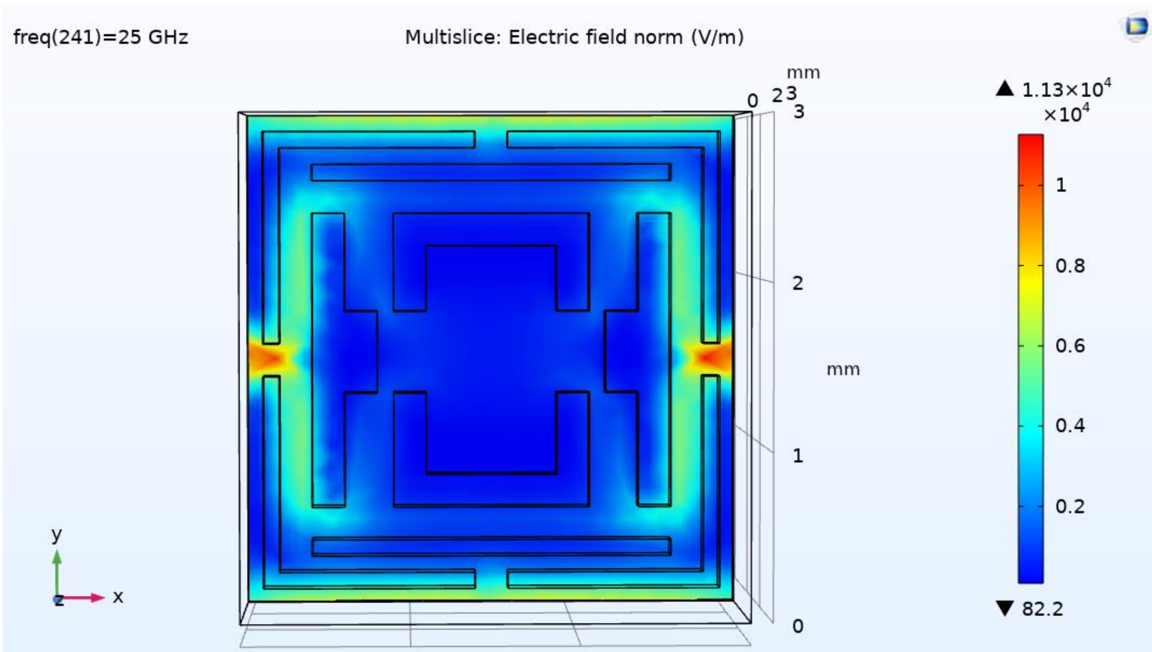

Fig:- 5.5 Electric Field Distribution in Design.

In this fig we conclude that the electric field is maximum in gap ($L1$) between the rectangular ring of the value 1.13×10^{3} V/m at frequency 25GHz. When increases the frequency t the confinement of the electric field is also increase. Due to the significant charge accumulation, there is a shift in the electric field distribution with frequency change, which causes the metamaterial structure to resonate in the frequency range.

5.3 REFLECTION PATTERN: The amount of electromagnetic energy reflected by a surface or contact when an electromagnetic wave impinges upon it is measured by the reflection coefficient. It measures the difference between the incident wave and the reflected wave(7). The complex ratio of the amplitudes of the incident wave (E_i) and the reflected wave (E_r) is how mathematicians define the reflection coefficient (ρ). It can be stated as follows:

$$\rho = \frac{E_r}{Ei}$$

Both magnitude and phase variants of the reflection coefficient are frequently used to depict it. The magnitude of the reflection coefficient ($|\rho|$), which normally ranges from 0 to 1, represents the amount of energy reflected. A reflection coefficient of 0 denotes total transmission (no reflection), while a value of 1 denotes complete transmission (no reflection). The phase of the reflection coefficient (arg (ρ)) shows the phase difference between the incident and reflected waves. Using electromagnetic field solvers like COMSOL, the reflection coefficient can be computed through simulation or determined empirically. In many applications, such as antennas, transmission lines, optical systems, and microwave circuits, it is a key characteristic used to describe the behavior of structures, devices, and interfaces.

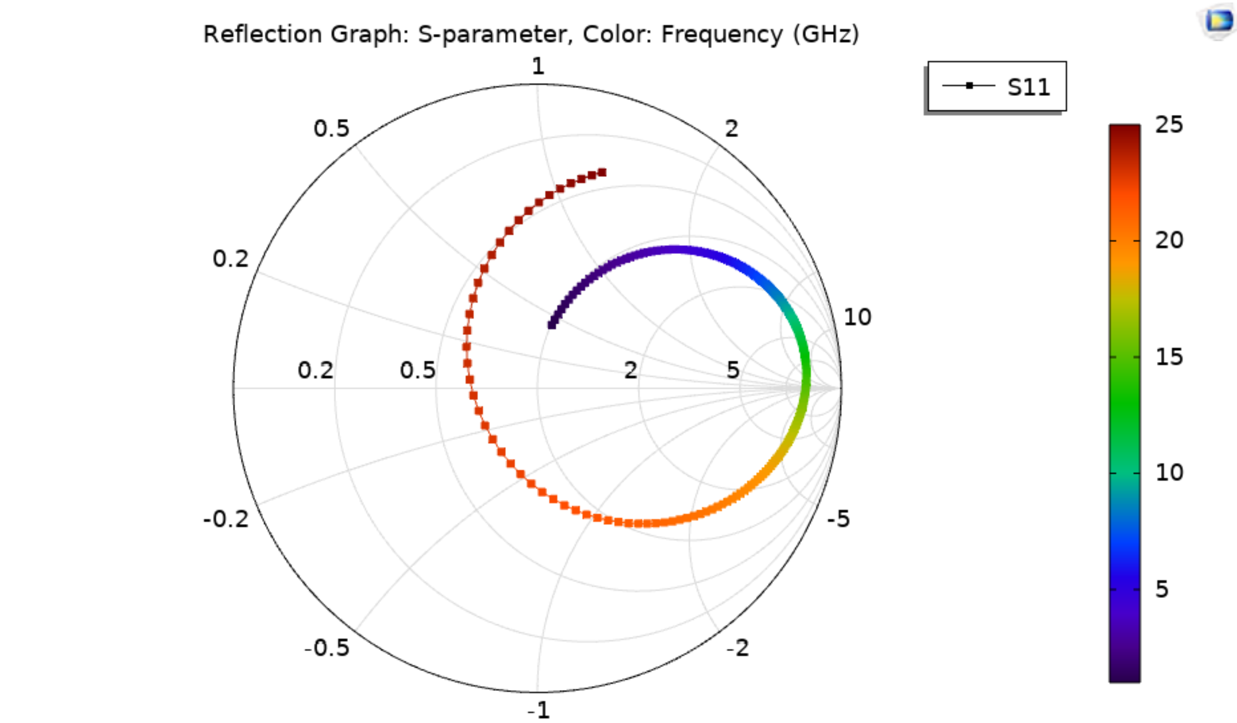

Fig:-5.6 Plot of Reflection

This graph show that how reflection of electromagnetic wave is increase on increasing the frequency.

The maximum reflection at a 25GHz.

The performance and impedance matching of a system can be understood by looking at the reflection coefficient. Maximum power transfer and fewer reflections occur in impedance-matched systems because the reflection coefficient is minimized. On the other hand, a high reflection coefficient denotes a mismatch between the source and load impedances, resulting in more reflections and perhaps worsening system performance.

CHAPTER 6

CONCLUSION

The investigation of a four-arm metamaterial reflector with frequencies spanning from 1 to 25 GHz was the main emphasis of this study, to sum up. This reflector design was built with copper arms and a FR4 substrate and then further optimized with COMSOL to provide remarkable frequency performance and little loss throughout the desired frequency range. Our study findings showed that the suggested reflector had a high level of reflection, with an amazing value of 88.97%. It can therefore reflect and control electromagnetic waves within the appropriate frequency range, proving its effectiveness. Such reflectors have a lot of promise for use in antennas, radar systems, and wireless communication devices, among other applications.

FIGURE CITATION

https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRZ1WVVNIDqzsh2p0JlAeOj5GsQY1p7guXm4A&usqp=CAU

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APPENDICES

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Certificate of Presentation

This certificate is proudly awarded to Prof./Dr./Mr./Ms. Neha Kumari
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Prof. Ranjana Jha
Conference Chair

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About ICAMET

The Department of Physics, Netaji Subhas University of Technology (formerly Netaji Subhas Institute of Technology) Delhi is organizing an International Conference on Advanced Materials for Emerging Technologies (ICAMET-2023) during May 04-06, 2023 in hybrid mode. The objective of this conference is to provide a common platform for all the researchers, academic personnels, scientists and research students from India and abroad to discuss and share their ideas, and research achievements related to advance materials and their applications for emerging technologies. The themes of the conference have been selected to accommodate a wide range of interests to facilitate interdisciplinary interactions among the participants.

Themes and sub-themes

- Functional Nanomaterials
- Metals, Alloys, Ceramics and Polymer
- Materials Synthesis & Characterization
- Optical/electronic/ magnetic materials
- Energy Materials and Devices
- Solar and Renewable Energy
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- Carbon Based Materials
- Hydrogen and Biomass Energy
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- Supercapacitors and Batteries
- Water Remediation / Treatment
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Registration fee

Students	: INR ₹2000
Faculty/Scientist	: INR ₹5000
Industry participants	: INR ₹6000
Foreign Delegates	: USD 200

•Registration fee will include registration kit, lunch, dinner, tea/coffee during sessions.

Important dates

Abstract submission closes	: 15 April 2023
Registration opens	: 16 April 2023
Registration closes	: 25 April 2023

Abstract submission

The abstract (max. one page as per template) shall be submitted through website: www.icamet.in

Further details regarding abstract submission and registration are available on conference

Website: www.icamet.in

e-mail: icamet@nsut.ac.in

The conference will be in hybrid (Online and Offline) mode. Abstract book will be published. The full length peer reviewed selected papers of ICAMET 2023 will be published in SCI/Scopus journal.

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There will be three cash awards for best oral and poster presentations in each category.

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Netaji Subhas University of Technology Delhi provide education and research in branches of engineering, technology, sciences, humanities, social sciences and management for the advancement of learning and dissemination of knowledge in such branches and for certain other matters connected therewith or incidental thereto. It has been consistently ranked as one of the top engineering institute in India and has featured prominently in various national level surveys conducted by reputed professional and trade magazines.

About Physics Department

The Department of Physics of Netaji Subhas University of Technology Delhi was established in the year 1983 under the School of Applied Sciences. It was created as a separate department in December 2013. The department primarily caters to the teaching requirement of various courses in Physics which form essential component of all undergraduate programmes in the first and second semester at the University. The department also offers M.Sc. Physics course of two years at PG level in addition to Ph.D. Programme.

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An exhibition will be organized during the conference. It will be aimed to prove an opportunity to the manufacturers/dealers of various instruments and its accessories to display their products for the participants of the conference. The exhibits may include technical literature books and equipment. Further, there will also an opportunity to include the advertisement in the souvenir/abstract book.

The tariffs for exhibition and souvenir advertisement are available on the conference website.