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POTENTIAL APPLICATIONS OF METAMATERIALS IN ANTENNA DESIGN, CLOAKING DEVICES, SENSORS AND SOLAR CELLS: A COMPREHENSIVE REVIEW

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This paper reviewed some of the applications of metamaterials in antenna design, cloaking devices, sensors and solar cells in brief. Metamaterials can be used as environment or as part of the antenna. Based on the required parameters, metamaterials while designing antennas are used in various types. They are highly useful in enhancing the power gain, bandwidth, in creating dense and antennas of multiple frequencies. Usage of metamaterial in antenna require proper designing of unit cell. This require creation of cells with special properties at required frequency. Cloaking is a technique of making specific objects invisible. This was achieved by isolating electromagnetic waves in that region. This paper reviewed some of the cloaking devices that use the technique of coordinate transformation and scattering cancellation. Metamaterial sensors which are more efficient than sensors with traditional materials are reviewed. These sensors exhibit enhanced sensitivity. Sensors used in wave guides and liquid chemical detection were reviewed. Solar cells that use metamaterials were reviewed. Usage of these materials reduce the loss in solar radiation making the solar cell more efficient based on the design. Recent design in solar cells concentrate on obtaining maximum reflection through usage of back reflectors and increased absorption.

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1. Introduction

Veselago,1968 a Russian physicist long back realized that properly tailored materials exhibit negative refraction [1]. He reported that materials whose permittivity and permeability values are negative exhibit characteristics of lenses. Since then after thirty years another physicist Pendry prepared such material [2]. There after many materials are tailored on continuous basis with negative permittivity and/or permeability. Depending on these materials variety of new applications that include antenna design, cloaking, superscattering, superabsorption etc. are proposed. Materials whose electromagnetic properties can be altered beyond their inherent nature are known to be metamaterials. Natural materials such as diamond or glass exhibit positive refractive index, electrical permittivity and magnetic permeability. Metamaterials tailored to have negative values of refractive index, permittivity and permeability are known to be NIMS (Negative Index Materials).These materials also exhibit reverse Doppler Effect.

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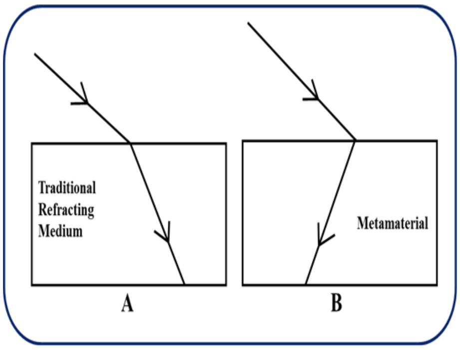

Fig. 1.Negative indexed metamaterial.

Fig. 1 indicates the property of a metamaterial in which permittivity and permeability are negative. Hence refractive index also negative. This is known as Left Handed Material since it follows Left Hand Rule. Negative refractive index can be obtained if both permittivity and permeability are negative. It is a known fact that either of these two will be possible but both negative simultaneously is not possible for any material. Hence materials need to be tailored for artificial characteristics mentioned above. These materials find wide range of applications that include antennas, cloaking devices, optical devices, sensors, solar cells etc.

2. **Metamaterial antennas**

Antennas made with metamaterials are light weight exhibiting high gain with electrically configurable beam of maximum channel efficiency. Their self alignment makes them highly potential with least technical installation and support wide range of frequency spectrum[3].In view of the existing special properties, usage of metamaterials in antenna design make them exhibit novel characteristics. A metamaterial antenna is a combination of one or more layers of substrates of metamaterials which improves the configuration of antenna in terms of performance. Reports indicate that usage of metamaterials in design of antenna enhances power radiated and reduces antenna size. Based on the design type and application metamaterial need to be selected. A metamaterial used in antenna design comprises of one unit cell or an assembly of many unit cells. To start within designing a metamaterial antenna is to analyse the components that influence a unit cells permittivity, permeability and resonance frequency [4]. The size and structure of each unit cell will determine different values of permittivity (ε),permeability (μ) *and* frequency at resonance (f).Resonant frequency fr condition can be satisfied through variation in cell dimension [5]. Here it should be noted that the necessary and sufficient condition for a metamaterial to satisfy the condition of homogeneity is that the size of cell should be much lesser than guided wavelength. Reports indicated that simulation of unit cells numerically could not attain results required. Hence, the cell sizes are continuously modified till simulation results assure the essentials of required structure. To obtain satisfactory output in less time, optimization computational algorithm is used to determine the size of unit cells yielding good results.

In designing compact antennas with frequencies in the range of radio and microwave, AMC's(artificial magnetic conductors) and HIS(high impedance surfaces) are reported to be morerelevant. However metamaterials are used as part of structure of the antenna system. The radiation properties of antennas can be improved by using AMC which is one class of applied metamaterial used in microwave applications. Microwave devices performance can be enhanced by using unique properties of metamaterials. However usage of AMC limits wideband antenna applications. Usage of AMC overcomes some limitations related to traditional antenna designs. Radiation properties of metamaterial antennas can be improved by placing the antenna above the reflector so that it radiates in only one direction and reduce back radiation [6].Here it should be noted that the metamaterial can be used as a device instead of medium to serve as an active substrate in creating plasma environment in every unit cell. AMC's are widely used metamaterials in designing antenna which simulate perfect magnetic conductors (PMC) that are not naturally available.The performance of antenna with AMC improvesas it simulates PMC’s ability of providing0^0reflection phases at resonance(Fig. 1) [7]

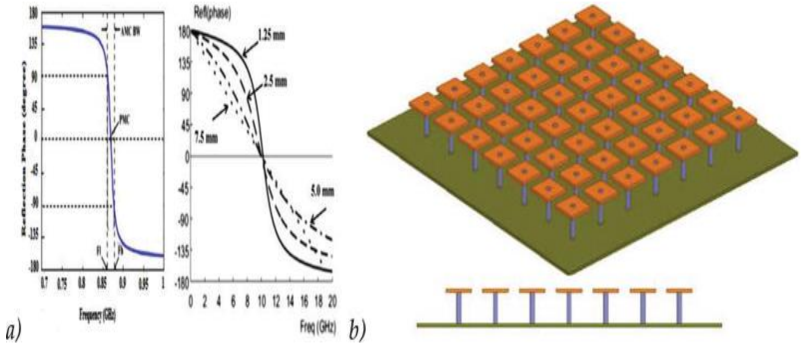

Fig. 1.a.Artificial Magnetic Conductors Phase Diagram; b.Surface design in the shape of mushroom, Courtesy: [3].

Designing compact antenna (patch antenna) can be done by building antenna structure with metamaterials. This does not reduce the performance efficiency provided the metamaterials used are of high permeability and act as magneto-dielectric (MD) substrate[8][9]. This results in significant reduction of antenna size without usage of high permittivity. Usage of metamaterials in designing of antenna may lead to size reduction, improved gain and bandwidth enhancement. Based on technical requirement metamaterials can be used as various functions in designing the antenna.

2.1. Antenna gain with metamaterials

The main disadvantage of small planar antenna is its low gain which must be addressed. In recent times metamaterial is being used in antenna design instead of using an array antenna.

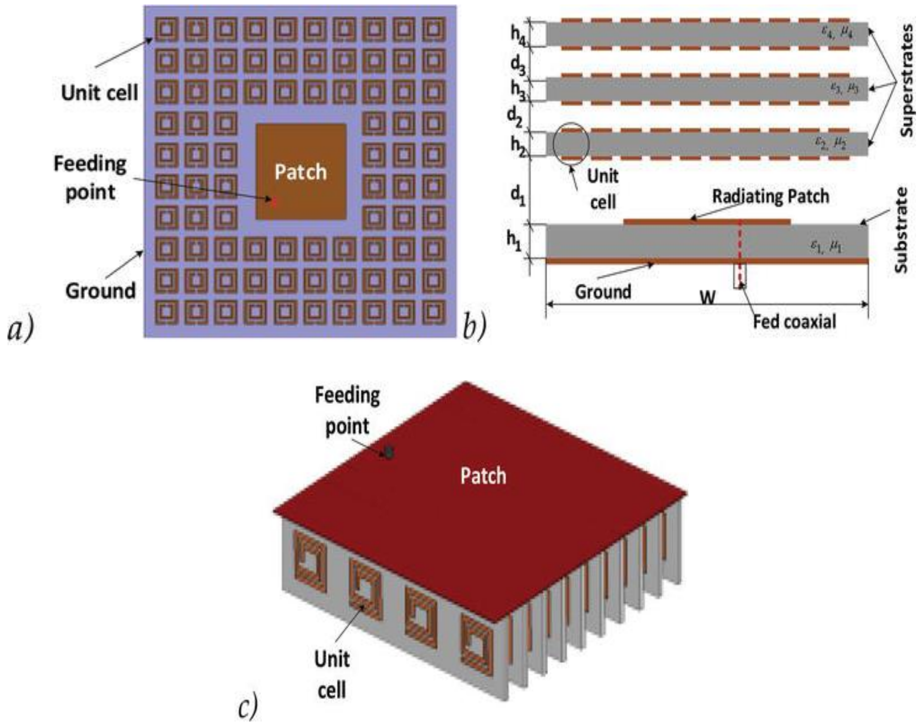

Fig.2. Metamaterial usage in antenna to improve power gain; a. Radiated patch surrounded by unit cells; b.c. Metamaterials as superstrate and antenna load Courtesy:[3].

The improvement of power gain depends on the superstrate number, type of unit cell and the gap between superstrate and radiation element. Arrangement of unit cells round the antennas radiation elements may load the substrate one or both sides. Hence their size must be estimated such that the metamaterials exhibit specific properties to match the antennas resonant frequency. Integration of unit cells with radiated elements is an easy process which can act as insulators by reflecting the surface waves depending on negative refractive index. The obtained antenna gain depend on unit cell number and resonant frequency. [11]. Designing of antennas with metamaterial superstrates significantly improves gain, also increasing the size and thickness of the antenna.Fig.3 shows plane fractal antenna along with power gain.

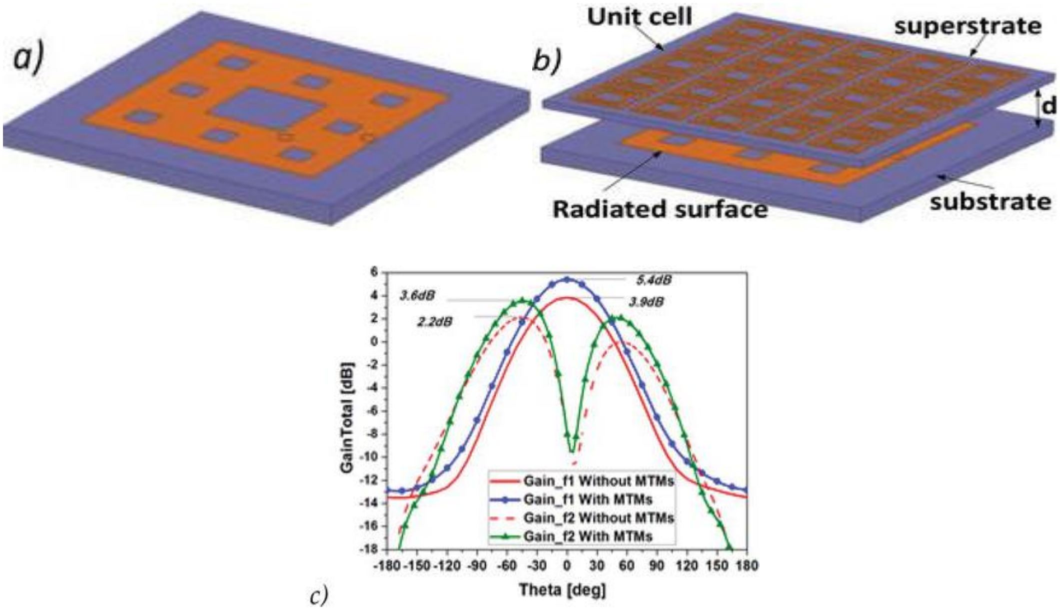

Fig. 3. a. Plane fractal antenna; b. Antenna covered with the AMC Metamaterial; c. Realised power gainfor two resonant frequenciesCourtesy: [3].

2.2. Increased bandwidth and reduced antenna size with metamaterials

Designing of compact antennas was done by using dielectric substrates high permittivity, fractal geometry, shorting of pins, shorting of walls, including interferences in its structure etc. Reports indicated designing of small sized metamaterial antennas with defected ground structures (DGS) in which the unit cells of size equal to removed parts of DGS and exhibit abnormal properties at resonance frequency[12]. Apart from the above benefits usage of metamaterials enhances the frequency bandwidth of the designed antenna. In this case they are used as antenna components (Fig.4) or as superstrate mentioned earlier. Unit cells located at superstrate decide bandwidth depending on the cell number and the proximity between superstrate and surface of radiation.

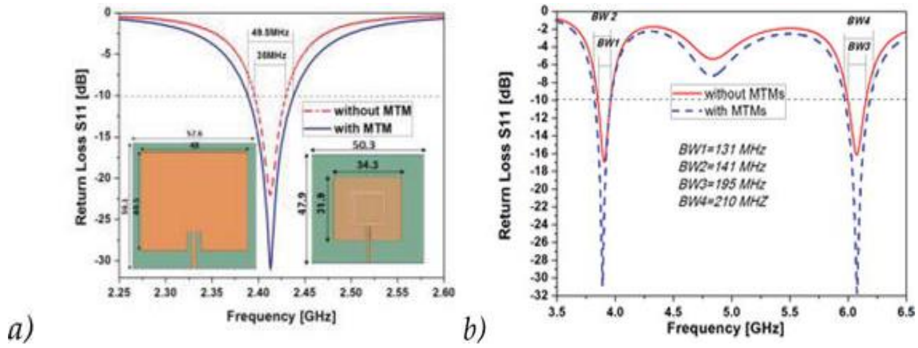

Fig.4.(a,b).Antenna's S-parameters without and with metamaterialCourtesy[3].

Based on the type of application usage of metamaterials as DGS decreases the antenna size and increases the bandwidth. Fig.4 shows two antennas with different size and bandwidths with and without metamaterial application for WLAN system of resonant frequency 2.413 GHz.

2.3. Multiband antennas with metamaterials

Integration of multiple communication systems on a single device gained significant interest giving rise to design of multiband antennas by using metamaterials. R. Rajkumar and K. Usha Kiran, 2016 indicated that multi-frequency antennas with lesser dimensions than regular ones can be designed with metamaterials as they support symmetric pairs with unit cell structure and negative refractive index at resonant frequency[13]. Combination of metamaterial with regular antenna leads to a multiband antenna whose size depends on lowest frequency. SabherDakhliet.al.,2016 reported a group of multiband dipole antennas designed with metamaterials which are based on plane dipoles with capacitive loops acting as near field resonant parasitic elements. The size of capacitive loop and their proximity with dipole determine the number of operating frequencies. They reported that the designed antennas exhibit multiband behaviour. They fabricated similar prototypes and tested which indicated that the simulated values and obtained results are highly correlated [14].

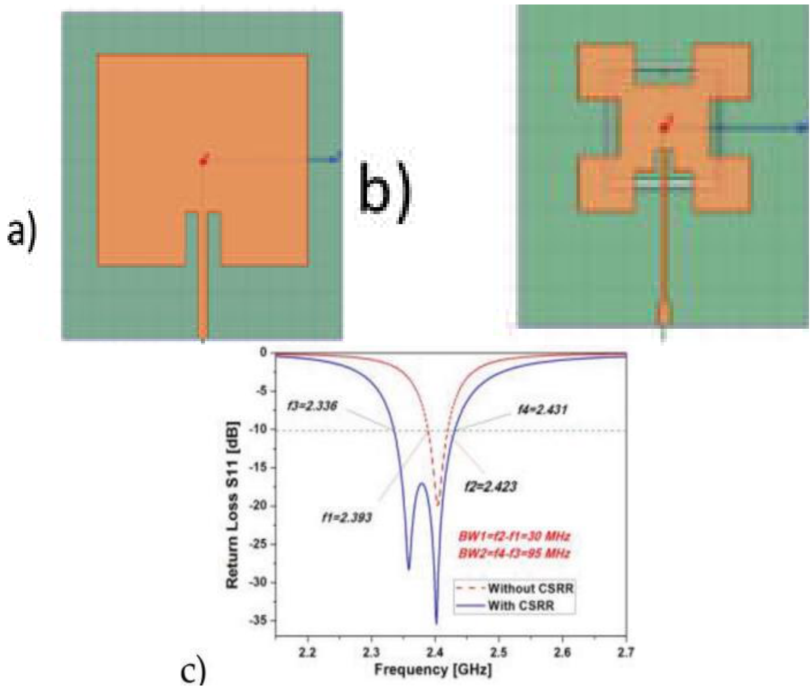

Fig.5.(a,b). Microstrip antenna without and with loaded CSRRc. S11 parameters Courtesy[3].

Fig.5 displays simulation model and scattering matrix coefficient (S11)for two antennas operating at different frequencies. Any change in antenna size or unit cell size will alter the resonant frequency.

3. Cloaking devices with metamaterials

Cloaking gained significance after developing different metamaterials. Various techniques are used in cloaking with acoustic or electromagnetic (em) waves such as coordinate transformation, scattering cancellation, transmission lines etc. Current research in cloaking focus on extending bandwidth for invisibility of specific or arbitrary objects and in extending these devices to operate in the range of optical frequency. Cloaking devices can isolate electromagnetic waves passing through a specified region so that the objects in that region are invisible. This is achieved by using metamaterials in creating blind spots by deflecting certain parts of the electromagnetic spectrum.

Cloaking is a method of making objects appear invisible by using metamaterials. It is similar to a magic show in which a magician do the same thing with mirrors. The object even though don't disappear it appears to vanish through illusion. This is done by using metamaterials by deflecting selected frequencies of light in the spectrum thereby creating blind spots[15]It is nothing but refraction or reflection of light that determine the illusion. Cloaking devices are of many types that include: Electromagnetic Cloak, Stealth Cloak etc.

3.1. Electromagnetic cloak

An electromagnetic cloak is a device which makes an object invisible for electromagnetic radiation in a certain frequency range. For an object to be invisible it should not reflect waves back to the source or scatter waves in any direction ie it should not disturb any exiting field outside the object[16].As per scattering theory of em waves reduction of scattering cross section [ratio of scattered power to incident power to zero leads to cloaking of object. of cloaks based on the technique of scattering cancellation depend on materials with relative permittivity less than 1. Gold and silver are materials with low permittivity in THz range, optical or infrared frequencies. These materials has limited utilization due to losses and significant variation in material properties with frequency. In this context report of Mario G Silveirinha et al.,2007 is of importance. They designed a metamaterial cloak using technique of scattering cancellation with metallic plates implanted parallel and located round the cylindrical region of a dielectric object which need to be cloaked [17]. Even though design of scattering cancellation technique is simple, drawbacks include the type of object to be cloaked and respective metamaterial required, limitation on bandwidth etc.

Leonhardt, 2006 and Pendry et al.,2006 described cloaking using metamaterials that create zero electromagnetic field inside a device[18][19]. They used a technique that depend on transformation of coordinates. Cloaking objects with this technique definitely require anisotropic metamaterials with relative permittivity and permeability values less than that of free space values. Generally the operation of passive cloaks is limited due to permittivity or permeability losses which are inherent to metamaterials leading to very narrow bandwidth at desired cloaking effect[20].It is also reported that simplifying of ideal values of permittivity and permeability leads to deteriorating of cloaking performance[21]. Alitalo P et.al.,2008 proposed a cloaking technique based on usage of volumetric structures with two or three dimensional transmission line networks [22] in which the electromagnetic fields propagate inside transmission lines, thus leaving the volume between these lines effectively cloaked. It has simple structure, can be easily fabricated and has wideband operation. The drawbacks in this approach include limitation on shape and size of the cloaked object.

3.2. Electromagnetic stealth cloak

Stealth generally refers to a technology of designing an aircraft which cannot be detected by a radar or sonar. Cloaking and stealth technology are two different concepts in which stealth technology will only reduce the reflecting power that was probed by radar. This is possible if the object is covered with an absorbing layer or shape the object in such a way that scattering field in the direction of illumination will get minimized. This technique hides the object only from front view. For example an ideal stealth aircraft can be seen from side or back. It is reported that covering and object shaping cannot reduce net scattering cross section more than 50%[23].Applications of electromagnetic stealth started with electromagnetic cloak which hide the object by guiding the path of em waves round the object and traces its original path instead of scattering outward. Hence the viewer cannot observe change of em wave so that the aircraft or flying object cannot be detected. The concept behind metamaterial electromagnetic stealth cloak was first reported by Pendryin 2006. Transformation optics theory was utilised to realize the objects stealth in the cloak. Variation in permeability and permittivity of metamaterial controls the direction of the em wave [24]. Reporting of electromagnetic stealth cloaks with metamaterials operating in microwave frequency range by D. Schurig et al.,2006ignited worldwide scientist to extensive research on this concept [25].Henceforth, various new devices like electromagnetic transparent body [26], electromagnetic focusing device[27],electromagnetic outer cloak [28][29]tunable metamaterial absorber [30] have been successfully reported with necessary simulations. In addition to commonly referred negative refractive materials(NIM), zero-index metamaterials (ZIM) also pose significant applications with less consideration. Guozhi Zhao et al.,2019 proposed a metamaterial with zero refraction with band width of 5.86GHz and studied their refractive index, surface current, permittivity and permeability. Property of zero refraction was verified they simulated a triangular prism electric field. A sample of 20 cm^2 surface from planar array was fabricated to measure electromagnetic parameters through free space method. This is used to design a rectangular cloak from which electromagnetic stealth at 2.2–4.3GHz frequency band has been achieved[31].They used the reflection cancellation principle for reduction of shadow behind the object. They reported that the basic structure of zero refraction metamaterial and rectangular stealth cloak design has rich deformation in structure and find potential applications in electromagnetic stealth field.

4.Metamaterial sensors

Life without sensors cannot be imagined. Sensors in residences, offices, cars and industries are providing good life by turning lights off and on, varying room temperature, detection of fire etc. Sensors are playing an important role in all sectors and can be fabricated using many materials. However sensors made of metamaterials gain tremendous significance in view of their advantages when compared to that made from other materials. Even though metamaterials exhibit certain losses limiting them for practical applications[32] this is not of importance for sensor applications. For example sensors can operate at single frequency and hence broadband materials are not required. Similarly the sharp resonant peaks in dispersion mean increased sensitivity of sensor. Zoran et al.,2007 indicated that large absorption loss in a metamaterial is practically of no importance in case of sensor[33]. In addition metamaterials can amplify vanishing waves making the sensor to possess high sensitivity and resolution[34].This property makes metamaterials highly potential in improving the performance of sensors.

Yadgar I et al.,2020 designed and fabricated a metamaterial based sensor that detect liquid chemicals between 8GHz to 12 GHz frequency band. They tested various designs with genetic algorithm embedded in CST microwave studi for optimization of resonator with required dimensions. The simulated and experimental results confirmed the sensor detecting different liquids like transformer, corn, cotton, olive oils, diesels, aniline doped ethyl-alcohol and benzene doped carbon tetrachloride by bringing a shift in the resonant frequency of about 50 MHz-250 MHz for the above liquids. This sensor can be used in detection of liquid chemicals and industrial applications[35]. Sajal Agarwal and Y.K.Prajapathi,2020 proposed a metamaterial based optical sensor for detection of sucrose. They optimized the sensor by fabricating a metamaterial surface with E-beam lithography technique with broad wavelength. The accuracy of detection and sensitivity of the sensor was found to be more than ordinary thin film sensor. The central wavelength of this sensor is 967nm which is higher than that compared to gold and metamaterial(933 nm) based sensor ensuring more bandwidth than that of a metamaterial based sensor. Also better sensitivity is recorded due to high ratio between surface and volume of metamaterial in this case[36]. In this context many metamaterial based sensors are proposed such as highly sensitive refractive index and temperature sensor based on semiconductor metamaterials in the terahertz range[37], metamaterial based sensor with polycarbonate substrate that sense the permittivity of alcoholic liquids in a wave guide [38], design and verification of narrow-band high-Q gas sensor [39] with single port that can be used for realtime environmental monitoring and gas concentration analysis with high sensitivity were reported.

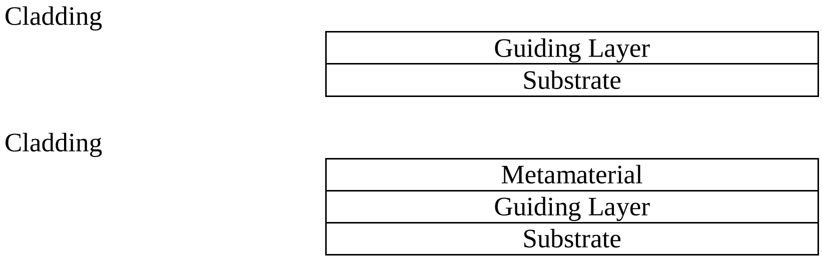

Fig. 6.a. Simulation Model of a conventional planar waveguide sensor; b.Planar waveguide sensor with metamaterial.

5. Solar cells with metamaterials

Metamaterials are well suited for use in solar cells. They are fabricated with broad band wide angle to match the solar spectrum making them highly potential to accept light in various angles reducing the reflected light and increasing the incident light. However they exhibit some disadvantages when used in solar cell since perfect absorption is within narrow band only. Also the absorption is less than ten percent for majority of the solar spectrum. Hence design of various types of absorbersis taken up in the direction of utilizing solar energy in effective way. Yang Liu et.al.,2012 reported innovation of solar cells with metamaterials. They carried out material, shape and parametric studies to obtain better absorption without loss in thermal energy. They indicated best absorption(77%) in solar spectrum and 84% in visible region for a semicircular solar cell when Ni and SiN are used as materials.[40]. Arup Dhar et al.,2018 reported silicon solar cells with metamaterial mirrors as back reflectors to obtain maximum reflection. In a regular metallic mirror light reflects with phase reversal decreasing the intensity which is undesirable in thin solar applications. To overcome this drawback a metamaterial mirror is used where no phase reversal of incident em wave takes place giving rise to maximum electric field at the mirror surface. This increase in electric field will lead to increased absorption in the thin solar absorber resulting in high efficiencies[41].

6. Conclusions

The potential applications of metamaterials was reviewed. Their role in antenna design, cloaking, sensors and solar cells was reviewed in a comprehensive way. The idea is to bring the latest applications of metamaterials reported in to a nut shell. It is observed that by tailoring metamaterials with various characteristics lead to highly potential applications. Even though they are already successful in antenna designing, cloaking which help in defence, solar cells for efficient usage of solar energy further research in designing and analysing novel metamaterials in the direction of drug delivery, nanomedicine has high scope.

In near future cloaking applications related to making human invisible will be reported. Based on the metamaterial tailored with different characteristics many more applications in various sectors continues. We hope that these materials play important role in medicine and drug delivery bringing nanomedicine into limelight.

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