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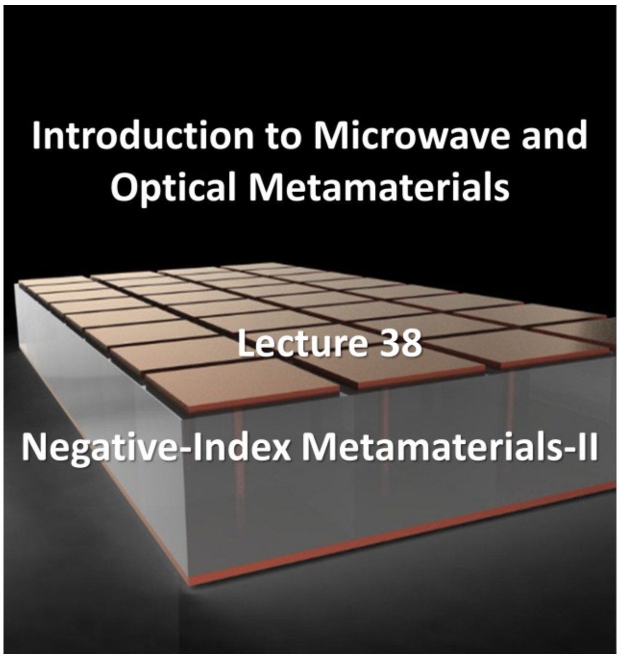
Week-8
Lecture-38

Lec 38: Super Resolution with Meta-Lenses



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Lecture Outline

- The Debut of Optical Negative-Index Materials
- Optical NIM using Paired Metal Nanorods
- General Recipe for Construction

Hello everyone, welcome to Lecture 38 of the online course on Introduction to Microwave and Optical

The Debut of Optical Negative-Index Materials

- Initial Discovery and Importance: Negative refraction was first observed in the microwave range. However, scaling it to the optical range is crucial for both theoretical understanding and practical applications.
- Challenges in Scaling:
  - Directly scaling down microwave NIM (Negative Index Material) structures to create optical NIMs isn't feasible
  - This is primarily due to significant fabrication challenges and fundamental material limitations
- Difference in Metal Behavior:
  - The electromagnetic response of metals in the optical range is vastly different than at lower frequencies, where ϵ is extremely large and metals behave as nearly perfect conductors
- New Approach for Optical NIMs:
  - The unique electromagnetic response of metals at optical frequencies allows for the excitation of a surface plasmon resonance
  - This phenomenon provides a new way to achieve the required negative permittivity and permeability for creating optical NIMs, a method not available at lower frequencies

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

The Debut of Optical Negative-Index Materials

- Experimental Characterization: A key challenge in optical Negative Index Material (NIM) research is the difficulty in experimentally verifying their properties, which is more complex than with microwave NIMs.
- Fabrication Limitations: Most reported optical NIMs are fabricated as thin, planar layers using techniques like optical or electron-beam lithography (this makes it impossible to perform standard experiments that rely on a bulk NIM structure)
- Inability to Directly Observe Negative Refraction:
  - Wedge-like structures: The thinness of optical NIMs prevents the direct observation of a negatively bent light beam, an experiment that was successfully conducted with microwave NIMs
  - Lateral displacement: Similarly, the subwavelength thickness of the NIM samples makes it impossible to observe the lateral shift of a light beam, another method used to verify negative refraction based on geometrical optics

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

The Debut of Optical Negative-Index Materials

- Ambiguity in Anisotropic Materials:
  - Poynting vector methods: Methods that rely on measuring the direction of the Poynting vector at inclined interfaces are not reliable for unambiguously determining the sign of the refractive index in anisotropic materials
  - Natural negative refraction: Negative refraction is an intrinsic property of some uniaxial media, and it has been observed in natural crystals such as calcite and yttrium orthovanadate (YVO_4)
- Overlapping Negative Responses: A NIM requires that the frequencies at which the material exhibits a negative electric response and a negative magnetic response overlap
- Achieving Negative Permittivity:
  - This can be achieved using artificial materials made of periodic metallic structures
  - The electric response of such a material can be designed to mimic the Lorentz model, where key frequency parameters (ω_0 and ω_p) are controlled by the geometry of the lattice and the metallic elements

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Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

Metamaterials. In today's lecture, we will continue our discussion on negative index metamaterials. Here is the lecture outline. We will have the discussion on the debut of optical negative index materials. We will discuss how we can make optical NIM negative index material using paired metal rods and nano rods. And then we will discuss the general recipe for construction.

So, let us first discuss the debut of optical negative-index materials. What is important? Because we need to understand the initial discovery and its importance, right? So, negative refraction was first observed in the microwave range. However, scaling it to the optical range is crucial for both theoretical understanding and various practical applications. Now there are some challenges in scaling.

So directly scaling down the microwave

The Debut of Optical Negative-Index Materials

- Combining Electric and Magnetic Responses:
  - The main challenge in demonstrating a NIM is properly combining the designed electric response with a magnetic response
  - A negative magnetic response has been extensively studied at gigahertz frequencies and higher
- The condition of simultaneously negative ϵ and μ from Veselago's seminal paper is sufficient but not necessary
- An alternative approach to achieving a negative refractive index in a passive medium is to design a material where the real and imaginary parts of the isotropic permittivity ($\epsilon = \epsilon' + i\epsilon''$) and isotropic permeability ($\mu = \mu' + i\mu''$) satisfy the following equation: $\epsilon'\mu'' + \mu'\epsilon'' < 0$
- This leads to a negative real part of the refractive index $n = n' + in'' = \sqrt{\varepsilon\mu}$
- The inequality above is always satisfied if both $\epsilon' < 0$ and $\mu' < 0$

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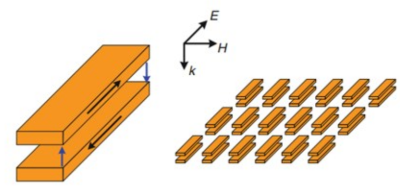
metamaterials or negative index material structures to create an optical version isn't feasible. And this is primarily due to significant fabrication challenges and fundamental material limitations. And there is also a difference in the metal behavior. Because the electromagnetic response of metals in optical range is vastly different than that at lower frequencies where ε is extremely large and the metals basically behave like nearly perfect conductors. Now, a new approach for optical negative index materials needs to be taken.

So, that will allow you to know the unique electromagnetic response of metals at optical frequencies that allows for the excitation of the surface + bond resonance. So, this phenomena could provide a new way to achieve or the required negative permittivity and permeability for creating optical negative index materials and this method is not available at microwave frequencies ok. So, if you look from the experimental characterization aspect, so a key challenge in optical negative index material research is basically the difficulty in experimentally verifying their properties. which is much more complex than with the microwave NIMs. And also there are fabrication limitations like most reported optical NIAMs are fabricated as thin planar layers using techniques like optical and e-beam lithography.

So, this makes it impossible to perform some standard experiments that rely on a bulk NIAM structure. So, it is not possible to directly observe negative

Optical NIM using Paired Metal Nanorods

- The necessary condition for an NIM can be achieved in an array of coupled nanorods
- It was shown in an early paper by Lagarkov and Sarychev that a pair of metal nanorods can have a large paramagnetic response
- Then, Podolskiy *et al.* showed that such a pair of metal nanorods is also capable of a diamagnetic response and, most importantly, negative n_0 in the optical range
- Following these theoretical predictions, the first optical metamaterial with a negative index of refraction was experimentally demonstrated by a research group at Purdue University using a layer of paired metal nanorods
- The building block of the metamaterial is a pair of nanorods, as illustrated in figure



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Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

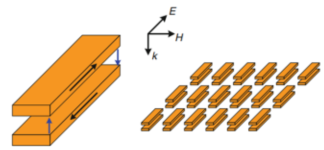
refraction. So you can think of some wedge-like structure. So here, the thinness of the optical NIMs prevents the direct observation of a negatively bent light beam. So that was an experiment that was successfully conducted in microwave NIMs but not in the optical domain.

Next is the lateral displacement that is like you know If you think similarly, the subweb length thickness of this NIMS sample will make it impossible to observe any lateral shift of the light beam. This was another method used to verify negative refraction based on geometrical optics. And then there is some ambiguity in anisotropic materials. So, methods that rely on measuring the direction of the pointing vector at inclined interfaces are not reliable for unambiguously determining you know the sign of the refractive index in anisotropic material. So, there is basically ambiguity in this kind of anisotropic material.

So, another thing is that there is natural negative refraction. That means you can observe negative refraction as an intrinsic property in some uniaxial media and it has been observed in some natural crystals such as calcite and yttrium orthovanadate or YVO4. So it is important to differentiate these properties with your negative index material and when you make Negative index material, it basically requires that the

Optical NIM using Paired Metal Nanorods

- An AC electric field parallel to both rods induces parallel currents in both rods
- The magnetic field, which is oriented perpendicular to the plane of the rods, causes anti-parallel currents in the two rods
- These anti-parallel currents cause the magnetic response of the system
- The magnetic response will be dia- or paramagnetic depending on whether the wavelength of the incoming magnetic field is shorter or longer than the magnetic resonance of the coupled rods
- The two parallel rods form an open current loop, which acts as a transmission line with a current resonance
- Such a current loop is closed at the ends of the rod-pair through the displacement current
- For normally-incident light with the electric field polarized along the rods and the magnetic field perpendicular to the pair, both the electric and the magnetic responses can experience resonant behavior at certain frequencies



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Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

frequencies at which the material is going to exhibit negative electric response, the same frequency it should also give you negative magnetic response, that means they should overlap, okay. So, this can be achieved by using artificial materials made of periodic metallic structures. So, as was basically done in the case of microwaves as well.

So, that is how you can achieve negative permittivity, right? So, the electric response of such material like periodic metallic structures can be designed to mimic the Lorentz model, where the key frequency parameters like ω naught and ω p is a resonant frequency and the plasma frequency can be controlled by the design of the lattice and the element itself. So, you can create your own material which has got a custom designed plasma frequency right and resonance. So, when you combine the electric and magnetic responses, the main challenge that you see in NIM is basically coming from there. So, you need to properly combine them, okay. So, you can say that a negative magnetic response has been extensively studied at gigahertz frequencies and higher, ok.

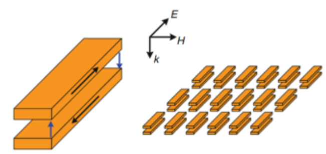
Like the condition for simultaneous negative ε and μ from the Vassilagos-Savignal paper is also reported to be sufficient, but not necessary. Now, there is an alternative approach to achieving this negative refractive index in a passive medium. and that could be to design a material where the real and the imaginary parts of the isotropic permittivity that is if you write ε as ε prime + i ε double prime so this is the real and the imaginary part and similarly if you do it for μ that is written as μ prime and i μ double prime, this is the real, this is the imaginary part, then that has to satisfy this condition that is ε prime μ double prime + μ prime ε double prime would be negative. Now, this would lead to a negative real part of the refractive index. So, your n which is basically n prime + i n double prime given a square root of ε and μ and when you have both ε prime and μ prime, ah negative you basically get that negative index.

So, now let us see how we can obtain optical negative-index material using paired metal nanorods. We have seen this kind of structure earlier. So, we will go into a little bit more detail here, okay. So, the necessary condition for a negative index material can be achieved in an area of coupled nanorods. So, it is shown in an early paper by Lagarkov and Sarichev that a pair of metal nanorods can have a large paramagnetic response.

And then Podolsky and his group showed that such pairs of metal nanorods are also capable of a diamagnetic response. And most importantly, they can give you a negative refractive index in the optical range. So following this kind of theoretical predictions, the first optical

Optical NIM using Paired Metal Nanorods

- Above the resonance frequency, the circular current in the pair of rods and the displacement current at the ends of the rods can lead to a magnetic field opposing the external magnetic field of the incident light
- In this design the electrical component of the incident wave excites a symmetric current mode in each rod pair, whereas the magnetic component excites an anti-symmetric mode



- The excitation of plasmon resonances for both the electric and the magnetic light components in an overlapping frequency range results in resonant behavior for the refractive index, which can become negative above the resonance as previously predicted
- This can be thought of as a resonance in an optical LC circuit, with the metal rods providing the inductance L and the dielectric gaps between the rods acting as capacitive elements C
- The sample was fabricated using electron-beam lithography

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Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

metamaterial with negative index of refraction was experimentally demonstrated by a research group at the Purdue University by using a layer of paired metal rods like this. So this is the building block of the metamaterial, which is nothing more than a pair of nanorods, as you can see here. So, there is an AC electric field parallel to the length of the rod.

So, you can see the electric field and the magnetic field directions here, and this is the direction of the wave falling from the top. So, you can see that an AC electric field, which is parallel to both rods, can basically induce parallel currents in both rods. And then you have the magnetic field, which is basically oriented perpendicular to the plane of the rods. That can cause, you know, antiparallel currents in the rods, okay. So, this antiparallel currents basically cause the magnetic response of the system right.

So, you have this kind of system, right? So, the magnetic response will be dia or paramagnetic depending on whether the wavelength of the incoming magnetic field is basically shorter or longer than the magnetic resonance of this coupled rods. Now, the two parallel rods basically form an open current loop that acts as a transmission line with a current resonance. Now, such a current loop is closed at the ends of the rod pair through the displacement currents. Now, for normally incident light which has got electric field polarized along the length of the rods and the magnetic field perpendicular to the rods, you will see that you know both the electric and magnetic responses can exhibit resonant behavior at certain frequencies. So above the resonance frequency, the circular current in this pair of rods and the displacement current that is at the end of the rods can lead to a magnetic field that is basically opposing the external magnetic field of the incident light.

So in this design, the electric component of the incident wave excites a symmetric current mode in each rod pair, whereas the magnetic component basically gives you anti-symmetric modes. So the excitation of the + 1 resonance for both the electric and the magnetic light component in an overlapping frequency range will result in a resonant behavior for the refractive index, which can become negative. above the frequency as was previously predicted right so this can be thought of as a resonance in an optical lc network so this will behave like the inductor and the gaps will behave like capacitors right so the metal rods can give you the inductance l and the dielectric gap between the rods can give you the capacitive element C. So, this kind of structure can be fabricated using e-beam lithography right. So, this is the designed unit cell of the paired nanorod array.

So, as you can see this one ok and this basically shows the field emission scanning electron microscope that is FESEM image of a portion of the sample and you can get a closer look here of a pair of nanorods how they look like. So, this is a single pair of nanorods and this is the pattern that is made and this is basically the unit cell that is repeated periodically and these are the dimensions mentioned here right. So, how do you get an optical NIM using these paired metal nanorods? So, you need to find the complex coefficients for transmittance and reflectance. That are needed for the retrieval of the refractive index, which can be measured directly in the paired nanorod experiments. So, you can obtain transmission t = the modulus of t squared and reflection r = the modulus of small r squared.

This factor can be collected with a spectrophotometer using linearly polarized light. okay and along with the experimental investigation the optical properties of the paired nanorods can also be studied from simulation using 3D FDDD or finite difference time domain methods, right. So, this particular figure basically illustrates the result for the phase measurements including the phase anisotropy and the absolute phase shift both of which are basically compared with the 3D FDDD simulations. So, this is the phase anisotropy δ φ in degrees, and this is wavelength on the x-axis. So, the phase anisotropy curve δ φ for the transmitted light, it shows a strong resonant behavior with negative value as much as - 100 degrees somewhere here around the communication wavelength of 1.

5 micrometer. So, these are the legends. So, you can see this represent phase anisotropy in the transmitted light simulated and then without the light only the circles are basically the experimental one. Similarly, here you have a square for the reflected light with the line and then only the square for the experimental one and so on. So, these two are for the transmitted and the reflected light and these are basically the absolute phase shift calculated for parallel polarization and then you have for perpendicular polarization.

So, it is a basic graph. So, we can go through it in steps and see what you will study from here.

So, if you look into the inset of the figure, you can see that the phase shift of the sample with respect to an air slab of the same thickness, there is a typo it should be just you know - 61 degrees at. So, this is for perpendicular polarization; this is for parallel polarization. So, perpendicular and parallel signs are mentioned here.

So, this is done at 1.5 micrometers. So, the magnitude of this value is 1.5. well below the phase shift in an air slab of 165 nanometer okay where you get φ r = 40 degree at 1.

5 micron. So that you know, you have the negative phase acquired in the sample to be around - 21 degrees. Now, this negative value basically indicates that you have a negative index of refraction, and that is for those particular wavelengths. So, your effective index of refraction is basically coming out as negative. So, this is a method to basically measure, along with the simulation, what the phase shift of the transmitted light is. Now, you can see that a high transmission of about 25 percent i

Optical NIM using Paired Metal Nanorods

- The designed unit cell of the paired nanorods array is shown in the figure (bottom left)
- Figure (bottom right) shows field emission scanning electron microscope (FE-SEM) images of a portion of the sample and a closer view of a single pair of nanorods

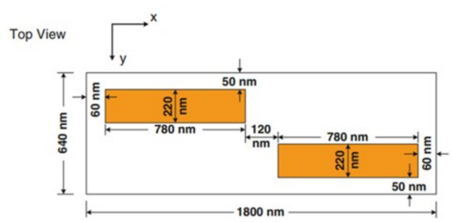

Fig. The designed elementary cell of the paired nanorod structure

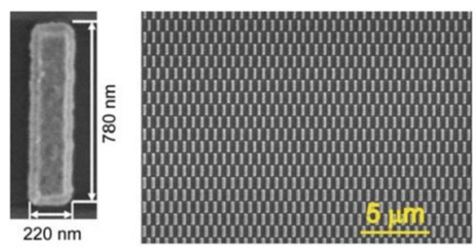

Fig. FE-SEM images of the fabricated array (top view)
Left: a single pair of nanorods, Right: a fragment of the pattern

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s obtained for 1.

5 microns. So, based on the effective parameter retrieval technique, you can obtain effective index of refraction for both the two polarization for reflection and

Optical NIM using Paired Metal Nanorods

- The complex coefficients for transmittance and reflectance needed for the retrieval of the refractive index were measured directly in the paired nanorod experiments
- The transmission T = $|t|^2$ and reflection $R = |r|^2$ spectra were collected with a spectrophotometer using linearly polarized light
- Along with the experimental investigation, the optical properties of the paired nanorod structure were also simulated based on a 3D finite-difference time domain (FDTD) method
- Figure illustrates the results for the phase measurements, including the phase anisotropy and the absolute phase shift, both of which are compared with 3D FDTD simulations
- The phase anisotropy curve $\Delta\varphi$ for transmitted light shows a strong resonant dependence with a negative value as much as $\sim -100°$ around the communication wavelengths of $\sim 1.5\ \mu m$

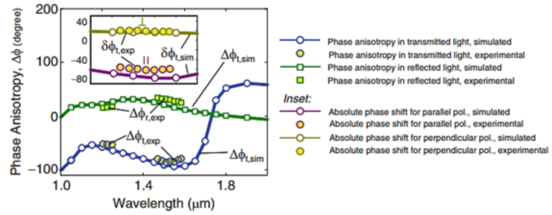


Fig. Experimental data for phase measurement along with simulations. Inset: absolute phase shift for transmitted light

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

transmission coefficients. So, this particular figure shows the zoomed view of the real part of the retrieved index of refraction using the experimental data and the simulation results. So, experimental studies of the nanorod sample provide a value of n which is - 0.

3 + or - 0.1 at 1.5 microns. So, this is the value; okay, this is the zoomed version shown here. So, this result is basically in good agreement with the simulation and experiment, as you can see there is a very good overlap here, okay. So, the optical negative index is actually possible ok in another kind of structure as well which is called the inverse of the coupled nanoroth structure. So, you can think of a inverse structure that is nothing but pair of elliptically shaped voids means holes that you are making on metallic films. So, in this case, a negative refractive index at about 2 microns was basically reported.

So, 2 micron is typically in the near infrared to mid IR range I think this is in NIR range anyways yeah it is close 1.5 and here you get 2. So, this is the structure, okay. So, this is the schematic. So, you are basically having these kinds of voids, and this is the SEM image, or scanning electron microscope image, of the structure.

So, what is happening here? So, in order to construct the coupled void structure ok, you need to begin with two thin films of metal which are basically separated by a dielectric spacer and then electrically shaped voids can be etched into the two metal films that can form paired elliptical voids okay. So, this basically creates the inverse of the original structure, which is basically paired metallic rods or ellipses, okay. So, in this both this kind of samples okay they should ideally exhibit similar resonance behavior if the orientation of the electric and the magnetic fields are basically So, here this is the direction of the wave falling, this is the direction of E field and H field. So, this is nothing but a result of the Babinet principle, which is useful to note here: an inverted NIM. inverted negative index material such as elliptical or dielectric or rectangular dielectric voids that you can make in a metallic film are basically physically equivalent to paired metallic rods which are embedded in a dielectric host.

So, this basically gives us increased flexibility in designing NIM structures that are actually reliable using current fabrication methods. So, because this one becomes easier to So, what are the general recipe for fabrication? So, while the two earliest optical negative index materials discussed have proven that you know negative index materials are indeed possible at optical frequencies. They both however, possessed you know significant losses which are indicated by large imaginary part n double prime that you see in the effective refractive index. Now, based on our discussion about the sufficient and the necessary conditions of the negative index of refraction, we can basically categorize the NIMs into two categories. First one is double negative NIMs in which the Veselago requirement of both negative negative real part of permittivity and negative real part of permeability is basically satisfied.

You can also have another type which is single negative negative index material where the condition the necessary condition that is ε prime μ double prime + μ prime ε double prime should be negative. So, this one is fulfilled, okay. However, you just have you know real part of the permittivity to be negative, but not of the permeability, permeability real part is positive. So, you can express the figure of merit of negative index materials in terms of the effective permittivity and permeability and it can be given like this FOM = - modulus μ ε prime + modulus ε μ prime / modulus μ ε double prime + modulus ε μ double prime. So, the NIMs that we have seen with pairs of nanorods and nanoboids, they are both belonging to this single negative index material class and they exhibit a low figure of merit.

Although both the negative ε prime and μ prime can be realized based on electric and magnetic resonances, respectively. It is not a good practice to combine the two types of plasmonic resonances at overlapping frequency ranges. The reason is first it is typically very difficult to obtain a system where both resonances will occur at the same frequency and second thing is that any plasmonic resonance will always bring loss to the system. So, since an electronic resonance it is not necessarily or you can say it is not really necessary in order to obtain you know negative ε prime, you should basically try avoid using a electric resonance in the design. So, a possible solution to this generic problem would be to just use a resonant magnetic structures along with a non-resonant metallic structure that basically provides a background negative permittivity / a broad spectral range including the wavelength band where you will see the magnetic resonance happening.

So, this is not hard to achieve because noble metals such as gold and silver, they have negative permittivities at optical frequencies below their plasma frequencies. So, just by adding a metallic film above and below a magnetic resonator for example, you can basically get the necessary negative permittivity for a negative index material. So, Zhao and his group proposed an alternative method to achieve this background negative permittivity. They proposed using pairs of continuous metallic wires that do not have electric resonances at that wavelength of interest. So, a magnetic resonance with a negative permeability can be obtained by including appropriately designed metallic pairs or plates.

So, the general guidelines above result ok. So, the general guidelines that we see here basically result in a fishnet kind of a structure that is also known as a double grading structure and which is today's prevailing structure for negative index materials for you know optical frequencies. So, you can think of this resonance structure which is having negative μ and this is having this is basically non-resonant structure means a broad / a broad frequency you can get this negative permittivity when you mix them together you get this fishnet kind of structure. Now, in the fishnet structure, the pairs of broader metallic strips basically provide the negative permittivity via asymmetric currents, whereas you can see that you know the pair of narrower metallic strips that is wears they act as diluted metal. So, the fishnet can be regarded as a resonant magnetic structure that is combined with a non-resonant electric structure. So, it is important to note that this fishnet structure The pair of narrower strips basically act as off resonant wires and at that wavelength where magnetic resonance basically occurs in the broader strips they simply provide a background negative permittivity.

So, based on this popular structure fishnet structure several groups around the world has demonstrated negative index of refraction in the near infrared and even the visible ranges. So, here is a SEM image of the fishnet structure that is discussed by Chettier and his group So, this sample was fabricated using standard e-beam lithography, e-beam evaporation and lift off process. So, this schematic of the unit cell of this fission structure is shown here along with the incident

Optical NIM using Paired Metal Nanorods

- From the inset of figure we can see that the phase shift of the sample with respect to an air slab of the same thickness is $\varphi_{s,\parallel} = -61°$ for light transmittance at 1.5 μm
- The magnitude of this value is well below the phase shift in an air slab of 165 nm $\varphi_r = 40°$ at 1.5 μm, so the negative phase acquired in the sample is $\varphi_s = -21°$
- This negative value indicates that the effective index of refraction is negative for the wavelengths
- Note that a rather high transmittance of about 25% is obtained at $\lambda \sim 1.5\ \mu m$
- Based on the effective parameter retrieval technique, we can obtain the effective index of refraction for two different polarizations using r and t coefficients

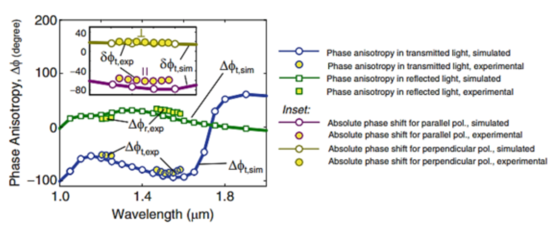


Fig. Experimental data for phase measurement along with simulations. Inset: absolute phase shift for transmitted light

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

polarization. Okay, in these two figures shown at 540 and 720 nanometers, respectively. So, what you see here is that the white one tells you about silver, and the bluish one is basically the alumina.

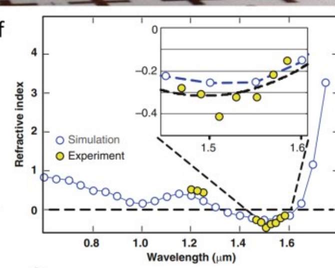
So, this is basically the fishnet structure; this is just a cut section to show you which material is which. So, the properties of the plasmonic resonance that you see in the structure can be visualized by simulating the field distribution in the sample at few interesting wavelengths. So, here you see the field maps the color basically tells you about the magnetic field and the arrows shows you the electric displacement right. So, the retrieved effective parameter for the fishnet sample is shown here. So, figure A clearly indicates that the electric behavior which is the real part of the permittivity beyond a electric resonance that comes around 540 okay similar to that of a dilute metal.

So, you can see it is just going down. Throughout, okay. And the magnetic resonance as you can see happens around 720 nanometer and it is giving rise to, so this blue one is basically the magnetic one. So, it is giving rise to a negative effective permeability, which is needed for double negative NIMs, right? So, So, in this particular figure b you can actually see that the negative index of about - 1 can be achieved around this wavelength which is 725 nanometer that corresponds to red light ok. So, this is as a byproduct at the other polarization of the same sample it will also display a single negative response which can be seen at slightly shorter wavelength of 710 nanometer and all. So, it is not surprising to notice that the FOM of the single negative band is only 0.5 which is basically much lower than the double negative one right.

So, that tells the story of how you can make negative-index

Optical NIM using Paired Metal Nanorods

- Figure shows the zoomed view of the real part of the retrieved index of refraction using experimental data and the simulated results
- Experimental studies of the nanorod sample provide a value of $n = -0.3 \pm 0.1$ at 1.5 μm
- The results indicate good agreement between measurements and simulations



- An optical negative index is also possible in the inverse of the coupled nanorod structure, that is, pairs of elliptically shaped voids in metal films
- A negative refractive index at about 2 μm was reported using such an inverse, resonant structure
- A schematic and a representative SEM image of such a geometry are illustrated in the figure

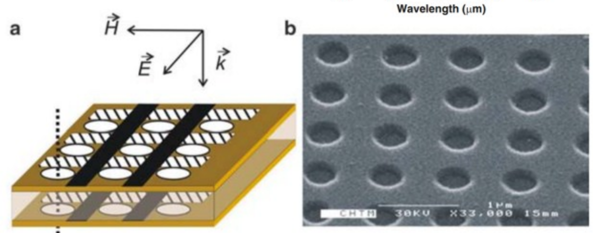
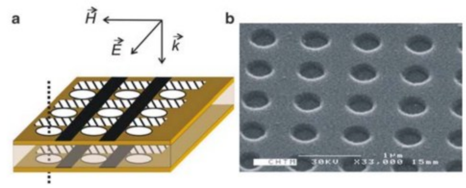


Fig. Schematic of the paired gold films with dielectric voids, (b) SEM picture of the structure

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

Optical NIM using Paired Metal Nanorods

- In order to construct the coupled-void structure, we begin with two thin films of metal separated by a dielectric spacer layer
- Then, elliptically shaped voids are etched in the two metal films to form the paired elliptical voids
- This creates the inverse of the original structure of paired metal ellipses



- However, both types of samples should exhibit similar resonance behaviors if the orientation of the electric and magnetic fields are also interchanged
- This is a result of the Babinet principle which is useful to note that, inverted NIMs such as elliptical or rectangular dielectric voids in metal films are physically equivalent to paired metal rods embedded in a dielectric host
- This gives us increased flexibility in designing NIM structures that are actually realizable with current fabrication methods

General Recipe for Construction

- While the two earliest optical NIMs discussed, have proven that NIMs are possible at optical frequencies, they both possessed significant losses as indicated by a very large imaginary part n'' in the effective refractive index
- Based on our discussion about the sufficient and necessary conditions for negative index of refraction, we can categorize NIMs into two types:
  - Double-negative NIMs (DN-NIMs) in which Veselago's requirement of both $\varepsilon' < 0$ and $\mu' < 0$ is satisfied
  - Single-negative NIMs (SN-NIMs) where only the necessary condition ($\epsilon'\mu'' + \mu'\epsilon'' < 0$) is fulfilled with $\varepsilon' < 0$ and $\mu' > 0$
- The FOM of NIMs can be expressed in terms of the effective permittivity and permeability:

$$\mathrm{FOM} = -\frac{|\mu|\varepsilon' + |\varepsilon|\mu'}{|\mu|\varepsilon'' + |\varepsilon|\mu''}$$

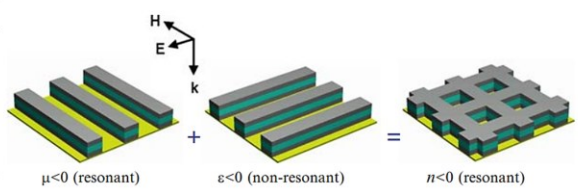
- The NIMs with pairs of nanorods and nanovoids both belong to the SN-NIM class, which inevitably exhibit a low figure of merit (FOM)

General Recipe for Construction

- Although both negative ε' and μ' can be realized based on electric and magnetic resonances, respectively, it is not a good practice to combine the two types of plasmonic resonances at an overlapping frequency range
  - First, it is typically very difficult to obtain a system where both resonances occur at the same frequency
  - Second, any plasmonic resonance always brings loss to the system
- Since an electric resonance is not really necessary in order to obtain a negative ε', we should try to avoid using an electric resonance in our design
- A possible solution to this generic problem is to use a resonant magnetic structure along with a non-resonant metallic structure that provides "background" negative permittivity in a broad spectral range, including the wavelength band where the magnetic resonance occurs
- This is not hard to achieve since noble metals like gold and silver have negative permittivities at optical frequencies below their plasma frequencies

General Recipe for Construction

- Hence, merely adding a metal film above and below the magnetic resonator, for example, should provide the necessary negative permittivity for a NIM
- Zhou *et al.* proposed an alternative method to achieve the background negative permittivity by using pairs of continuous metal wires that do not have an electrical resonance at the wavelength of interest
- Then a magnetic resonance with a negative permeability is obtained by including appropriately designed pairs of metallic wires or plates
- The general guidelines above result in the "fishnet" structure, also known as the double-grating structure, which is today's prevailing structure for negative index metamaterials at optical frequencies

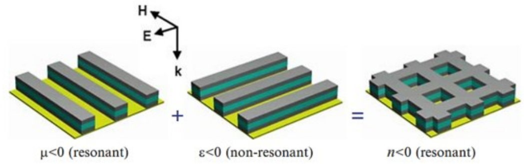


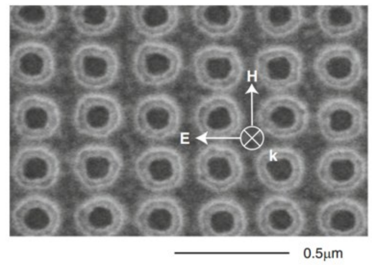
- In the fishnet structure, the pairs of broader metal strips provide negative permeability via asymmetric currents, whereas the pairs of narrower metal strips (wires) act as a diluted metal

IIT Guwahati | NPTEL swayam Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

General Recipe for Construction

- The fishnet can be viewed as a resonant magnetic structure combined with a non-resonant electric structure
- It is important to note that in the fishnet structure (figure), the pairs of narrower strips act as such off-resonant wires and, at the wavelength where the magnetic resonance occurs in the broader strips, they simply provide a background negative permittivity
- Based on the fishnet structure, several groups around the world have demonstrated a negative index of refraction in the near-infrared and the visible ranges
- The SEM image of the fishnet structure discussed by Chettiar *et al.* is shown in the figure





Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

General Recipe for Construction

- The sample is fabricated using standard e-beam lithography, e-beam evaporation and lift-off processes
- A schematic of a unit cell of the fishnet structure along with the incident polarization is illustrated in the figure
- The properties of the plasmonic resonances in the structure can be visualized by simulating the field distribution in the sample at a few interesting wavelengths
- In the field maps, the color depicts the magnetic field, while the arrows show the electric displacement

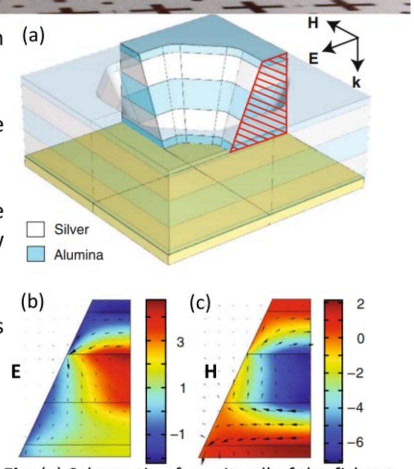


Fig. (a) Schematic of a unit cell of the fishnet structure, (b) and (c) show the field maps of the region marked with red lines in (a) at wavelengths of 540 and 720 nm, respectively

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

General Recipe for Construction

- The retrieved effective parameters for the fishnet sample are plotted as shown in figure
- Fig. (a) clearly indicates that the electric behavior beyond the electric resonance of $\sim$540 nm is similar to that of a dilute metal
- The magnetic resonance at $\sim$720 nm gives rise to a negative effective permeability, which is necessary for a DN-NIM

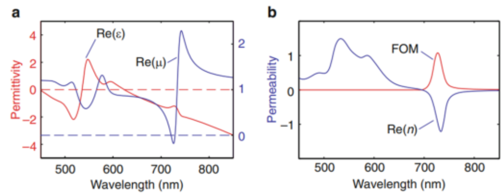


Fig. For the DN-NIM sample (a) Real parts of ε and μ, (b) Real part of η and figure of merit (FOM)

- Fig. (b) reveals a negative index of about -1 along with an FOM of above 1 at a wavelength of 725 nm, corresponding to red light
- As a “by-product,” at the other polarization the same sample also displays a single-negative response at the slightly shorter wavelength of 710 nm
- Not surprisingly, the FOM of the single-negative band is 0.5, much lower than that of the double-negative band

Source: W. Cai and V. Shalaev, Optical metamaterials, Springer US, 2011.

metamaterials at optical frequencies. So, with that, we conclude this lecture. If you have got any doubt regarding this lecture, you can drop an email to this email address mentioning the course name and the lecture number on the subject line.

Send your queries at deb.sikdar@iitg.ac.in

Slides inserted by fallback (review if needed):

Optical NIM using Paired Metal Nanorods

- The designed unit cell of the paired nanorods array is shown in the figure (bottom left)
- Figure (bottom right) shows field emission scanning electron microscope (FE-SEM) images of a portion of the sample and a closer view of a single pair of nanorods

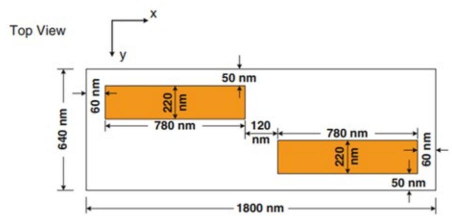


Fig. The designed elementary cell of the paired nanorod structure

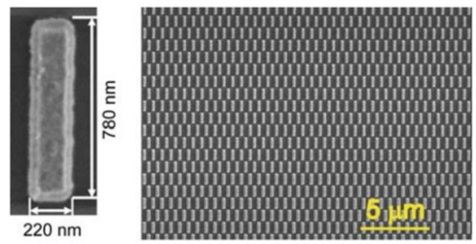


Fig. FE-SEM images of the fabricated array (top view)
Left: a single pair of nanorods, Right: a fragment of the pattern

Thank You