Course Name: Introduction to Microwave and Optical Metamaterials
Professor Name: Dr. Debabrata Sikdar
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-8
Lecture-39

Lec 39: Negative Index Metamaterials-II

Lecture Outline

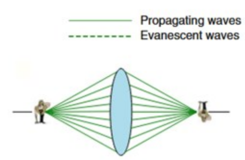
- Super Resolution with Meta-Lenses
  - Resolution Limit in Conventional Lenses
  - Perfect Lens with Subwavelength Resolution
    - ✓ How a Negative Index Materials (NIMs) Lens Works
    - ✓ Limitations of NIM Lens
  - Near-Field Superlens (NFSL)
  - "Tunable" Superlens using Random Composites
    - ✓ Principle of Tunable NFSL Operation

Hello everyone, welcome to Lecture 39 of the online course on Introduction to Microwave and Optical

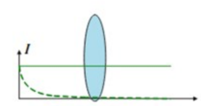
Resolution Limit in Conventional Lenses

- Resolution Limit in Conventional Lenses:
  - Based on positive-index curved surfaces (e.g., convex lens) → limited by Abbe diffraction limit.
    - ✓ Resolution limit $(\delta) \approx \lambda_0 / (2n \sin\alpha)$; where-

      n = refractive index of medium, α = semi-aperture angle of lens
  - Cannot resolve objects smaller than ~ half of the illuminating wavelength $(\lambda_0/2)$.
  - Evanescent waves (sub-wavelength details) decay and cannot be restored.
  - Can only form images with wavelength-scale resolution.



Conventional lens collects the propagating waves



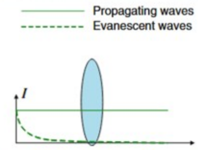
Loss of the evanescent waves in conventional imaging system

- Key Advantage of using Negative Index Materials (NIMs):
  - A planar slab with a refractive index of $n = -1$ placed in a vacuum could enable imaging with sub-wavelength precision.
  - This capability goes beyond the diffraction limit of conventional lenses.

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

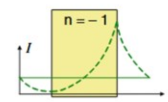
Resolution Limit in Conventional Lenses

- Wave Decomposition (Fourier Components):
  - Object scatters light into components with wavevectors (k_x, k_y, k_z).
  - The wavevector in the propagating direction: $k_z = \sqrt{k_0^2 - k_x^2 - k_y^2}$; where k_0 is the free-space wavevector
  - Transverse wavevector: $k_t = \sqrt{k_x^2 + k_y^2}$



Loss of the evanescent waves in conventional lens system

- Propagating condition: if $k_t < k_0$, then k_z is real → wave propagates normally.
  - **Propagating waves** can travel and carry information about the object's larger features.
- Evanescent condition: if $k_t > k_0$, then k_z becomes imaginary → wave decays exponentially.
  - **Evanescent Waves**: Confined to the near-field (close to object).
    - ✓ Carries sub-wavelength information (fine object details).
    - ✓ Lost in standard imaging, since conventional lenses cannot capture or restore them.



Growth of evanescent waves in NIM slab

- NIMs perfect lenses overcome the diffraction limit by restoring evanescent waves → enabling true sub-wavelength imaging.

Resolution Limit in Conventional Lenses

- Resolution Implication:
  - To resolve fine details, the transverse wavelength: $\lambda_t = 2\pi/k_t$ must be smaller than object feature size.
  - Since, for propagating waves: max $(k_t) = k_0$, the highest possible resolution is λ_0.
  - Conventional lenses cannot restore the evanescent waves that carry the sub-wavelength information, thus they are bound by this limit.
  - Therefore, conventional imaging systems cannot achieve sub-wavelength resolution.
- Overcoming the Diffraction Limit with NIM Lenses:
  - **Near-Field Microscopy Approach**
    - ✓ Subwavelength details carried by evanescent waves decay quickly.
    - ✓ Near-field scanning optical microscopy (NSOM): collects evanescent waves using a probe placed extremely close to the sample surface.
    - ✓ Before Pendry's idea, this was the only practical way to capture evanescent modes.
- In 2000, J. B. Pendry proposed a groundbreaking idea that a **negative index material (NIM) slab** could produce perfect images by amplifying these evanescent waves.

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

Metamaterials. Today's lecture will be on super-resolution with metal lenses. Here is the lecture outline, we will discuss about the super resolution of metal lenses, talk about the resolution limit in the conventional lenses. We will also discuss about perfect lens with subweb length resolution and then how a negative index material or NIMS lens basically works and we will also see the limitations of such lenses. And then finally, we will go to the discussion of the near-field superlens. We will see how we can make tunable super lens using random composites and what will be the principle of tunable near field super lens operation.

So, the first discussion will be on the resolution limit of conventional lenses. And I believe you have studied this in optics or physics that based on any positive index curved surface such as this convex lens, the resolution is basically limited by the Abbe diffraction limit. Now, what is that limit? It says that the resolution limit, or δ, is typically around λ naught / 2n sin α. where n is basically the refractive index of the medium and α is the semi-aperture angle of the lens.

Now, it tells you that a normal lens cannot resolve objects smaller than half of the illuminating wavelength, which is $\lambda / 2$. Okay, so that is the typical limit. Now, why does it happen? If you look through a conventional lens, this is how it basically collects the propagating waves. Okay, the solid lines indicate the propagating waves, and that is how the image is formed. Now, if you see that any object basically has two kinds of waves coming out of it.

One is the propagating wave; the other is the evanescent wave. Now, these evanescent waves basically contain the sub-wavelength details, and typically they decay and cannot be restored. And that is why you basically only see the image formed by the wavelength scale resolution. Okay, that is from the propagating wave. Now, this is where your negative index materials, or NIMs, will play a big role.

If you introduce a planar slab of refractive index of say $n = -1$ and you place it in the vacuum that will basically allow you imaging with subweb length precision. Now, this capability goes beyond the diffraction limit of the conventional lenses and we will see this in this particular slide. So, to understand how it works, we just go for the wave decomposition that tells us about the Fourier components present in the wave. So we can consider any object that scatters light and has components of the wave factors in all three directions. So you can mark them as kx, ky, and kz.

Now, the wave vector that is in the propagation direction you can consider z as a propagation direction. So, kz will be the square root of k_0 squared - kx squared - ky squared; k_0 is basically the free space wave vector. Now, you can denote kt as the square root of kx squared + ky squared, and that is basically the transverse wave vector. Now, what is the condition for propagation? So, if you have kt, which is less than k_0 squared, then this term is going to be a real quantity. So, kz is real; that means the wave is propagating normally.

So, here you can see that the propagating waves can basically travel and carry information about the object's large features. So, there is no issue, but If you look into the evanescent condition, that is where you know the kt is basically greater than k_0. That means the transverse wave vector is basically the, it is larger than the free space wave vector k_0. And in that case, your kz becomes imaginary. And that is the way where waves cannot propagate; rather, they decay exponentially.

And this is where the information of the sub-wavelength feature gets lost, okay. So evanescent waves, they are basically confined to the near field or you can say very close to the object and they carry subweb length information that means very fine details of the object and typically they are lost in standard imaging since conventional lenses are unable to capture or restore these waves. And this is exactly where this negative index material will perfectly fit in. And you can make perfect lenses based on them where you can place this to now restore the evanescent waves because evanescent waves basically grow in this kind of negative index material instead of getting decayed. So now you can see that you can actually restore it to the same level it was at earlier, and then it basically enables.

True sub-wavelength imaging is okay. So, in conventional lenses just remember that they lose this fine details due to the diffraction and that is mainly because of the evanescent waves are not being allowed to propagate or restored. So, to resolve the fine details or to have very good resolution we understood that the transverse wavelength that is λ t should be equal to 2 π/k t that must be smaller than the object feature size. Now, since for propagating waves we have seen that the maximum of the transverse wave factor kT will be equal to k_0 that means the highest possible resolution is basically λ_0. Now, conventional lenses cannot restore the evanescent waves that carry the sub-wavelength information thus they are basically you know bound by this diffraction limit or resolution limit.

Right. So, you can say you know that these conventional imaging systems cannot achieve sub-wavelength resolution. Now, we can overcome the diffraction limit using negative index material lenses, and this is where the near field microscopy approach is used. So, subweb length details as I mentioned they are carried by evanescent waves and they decay very quickly and If you look into the near field of scanning optical microscopy that is ANSOM, it basically collects the evanescent waves using a probe that is placed extremely close to the sample surface. And before Penry's idea of introducing that slab of material containing negative refractive index, this was the only practical way this ANSOM was only useful and practical way to capture this evanescent modes. However, in 2000 when Sir John Pantry proposed this groundbreaking idea that if you put a negative index material slab that is a NIM slab that can actually produce perfect images by amplifying these evanescent waves.

So, that became very popular, right? So, this is how we understand that you can use a perfect lens with sub-wavelength resolution. So what are these perfect lenses made of? They are made from negative-index materials. So, a perfect lens is a striking application of negative index materials. So a planar slab of NIM can function as a lens. Often it is also called the Veselago lens because he was the first one to theoretically propose the idea of this negative refractive index.

Okay, so what is striking or exciting here is that unlike a conventional lens, this kind of lens, vesilago lens or perfect lens, it has no axis or curvature. It does not focus the parallel rays or magnify the objects. So, it is just a rectangular slab, isn't it? So, how it works, you can see here. So, when light rays from an object enter a negative index material from the free space they are basically negatively refracted ok at the first instance ok. So, then again when they go to the second interface, you have another negative refraction that focuses them back.

So what is happening in this kind of slab is that it is forming two images. So here you are getting a real non-inverted images inside the slab and you can get a second non-inverted image in the free space after the slab. So, this is how you are basically getting the negative index material to work for you. Now, while doing so, this is basically how the propagating wave is progressing. We have already seen that you can use this material for restoring the evanescent waves.

So, when the evanescent wave enters this material, it is already in a very very weak form, but then because it grows exponentially in this material, it goes up to this level. But then again when the wave exits and come to free space it decays, but the good thing is at this particular point the level of that or the strength of that wave is of that mode evanescent mode is exactly same as what was there earlier. So, you actually have the same information; whatever information you have here is again what you are having here, and you are not losing anything. So, in negative index materials, lengths basically overcome the diffraction limit by a unique mechanism that could restore the evanescent wave we just discussed. So, what is the behavior of the evanescent wave? In free space, the evanescent wave basically decays exponentially with distance.

So, you can express this in the form of exponential - i ω t + i. k z z ok. So, their wave factor component is basically k z which is nothing, but i kappa z and that is coming as i square root of k x square + k y square - k_0 square right. So, they are basically decaying near fields ok and you can see that you know this particular term is imaginary and positive. So, the field is basically decaying Now, inside negative index material this evanescent fields get amplified and that is happening because in that case the k z which is nothing but - i kappa z will be written as - i square root of k x square + k y square - ε μ ω square by c square.

So, this is negative imaginary right. So, that is happening because you have both ε and μ negative in negative index material. So, their product will remain positive, and this term you are getting is negative imaginary. So, what happens when you get negative imaginary? That means the evanescent wave basically grows exponentially inside your negative index material slab. You get the function to become exponential, kzz.

So, this growth basically fully compensates for their decay in the free space and you can restore the evanescent mode at the imaging plane to their original amplitude ok, which are basically carrying the sub wavelength information and you can do the perfect imaging as we discussed right and shown in the earlier slides. So, for the propagating waves, which basically carry larger scale information, they also behave differently in a negative index material. their amplitude basically remains constant, but their phase k z = - square root of ε μ ω square by c square - k x square - k y square basically is getting reversed. So, this basically causes their phase to accumulate to 0. From the object to the image plane, okay? So, you are getting a perfect image because both your

Perfect Lens with Subwavelength Resolution

- A perfect lens can be made from negative index materials (NIMs).
- Perfect Lens and Veselago's Lens:
  - A perfect lens is a striking application of negative index materials (NIMs).
  - A planar slab of a NIM can function as a lens, often called a Veselago lens.
  - Unlike a conventional lens, it has no axis or curvature, and it does not focus parallel rays or magnify objects.
- Operating Principle:
  - When light rays from an object enter a NIM from free space, they are negatively refracted at the first interface.
  - This negative refraction occurs again at the second interface.
  - The NIM slab forms two images: a real, non-inverted image inside the slab and a second non-inverted image in the free space after the slab.

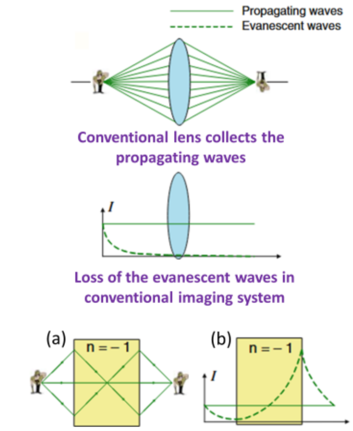


Fig. 1: Operation of NIM slab lens (a) The focusing ability of a NIM slab (b) Growth of evanescent waves in NIM slab and the restoration of both the propagating and evanescent waves

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

How a NIM Lens Works

- A NIM lens overcomes the diffraction limit by a unique mechanism that restores evanescent waves.
  - **Evanescent Wave Behavior:** In free space, evanescent waves decay exponentially with distance; can be expressed as: $\exp(-i\omega t + ik_z z)$
    - ✓ Their wavevector component: $k_z = i\kappa_z = i\sqrt{k_x^2 + k_y^2 - k_0^2}$; so decaying near fields; $k_z > 0$.
  - **Amplification in NIMs:** In a NIM, the evanescent wavevector: $k_z = -i\kappa_z = -i\sqrt{k_x^2 + k_y^2 - \frac{\varepsilon\mu\omega^2}{c^2}}$.
    - ✓ In NIMs, material parameters $\mu < 0$ and $\varepsilon < 0$, thus their product remains positive.
    - ✓ Consequently, the evanescent waves grow exponentially inside a NIM slab, following the functions $\exp(k_z z)$. This growth fully compensates for their decay in free space.
    - ✓ Thus, evanescent waves are restored at the imaging plane to their original amplitude, carrying the sub-wavelength details of the object.
    - ✓ Propagating waves: amplitude constant, phase $\left(k_z = -\sqrt{\frac{\varepsilon\mu\omega^2}{c^2} - k_x^2 - k_y^2}\right)$ reversed; net phase shift = 0.
  - Perfect Image: Because both propagating and evanescent waves are fully recovered, an ideal NIM lens can produce a resolution far below the diffraction limit.

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

propagating and evanescent waves are fully recovered and an ideal negative index material lens can produce a resolution which is far below the diffraction limit.

But there are some

Limitations of NIM Lens

- Pendry's perfect lens is a theoretical breakthrough showing that evanescent waves can be amplified for super-resolution imaging.

- **Practical Limitations**
  - Perfect lens conditions are extremely strict:
    - ✓ Must be lossless, isotropic, impedance-matched.
  - Since, realistic metamaterials are dissipative and lossy (plasmonic resonances).
  - Despite the theoretical possibility of a **perfect lens**, achieving one is extremely difficult.
  - Any real-world losses, anisotropy, or impedance mismatch in NIMs (which are all Irresistible in current designs) can eliminate the desired effect.
  - The NIMs created so far are highly dissipative and lossy.
  - This is why there has been no far-field demonstration of super-resolution using a planar NIM slab, except for a few fundamental results in the microwave range.

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

limitations to negative index material lenses as well. So we will discuss that. So, Pandry's perfect lens is basically a theoretical breakthrough showing that evanescent waves can be amplified for super-resolution imaging. Now there are some practical limitations because perfect lens conditions are extremely strict. First of all, they must be lossless, isotropic, and impedance-matched.

Now, since realistic

Near-Field Superlens

- A simpler version of the perfect lens, called the **near-field superlens (NFSL),** can achieve sub-wavelength resolution.

- This design is easier to realize because it doesn't require negative permeability (optical magnetism).

How it Works

- The NFSL is based on the **quasi-static approximation**, which applies when all system dimensions are much smaller than the wavelength.

- Under this condition, the requirement for superlensing of p-polarized (TM mode) waves is simplified to the condition that:
  - The lens's permittivity (ε) must be equal to the negative of the host medium's permittivity (ε_h) (i.e., $\varepsilon = -\varepsilon_h$).

- **No optical magnetism needed:** Simplifies design compared to full NIM.

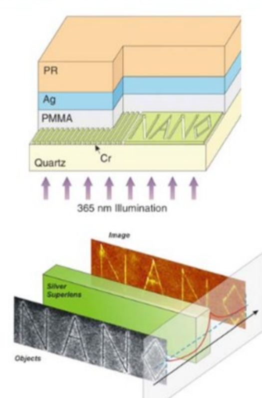

Fig. 2: Optical superlensing with a silver slab operating at a near-ultraviolet wavelength

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

Near-Field Superlens

Material Choice

- Since an NFSL only needs a negative permittivity, it can be made from a material with a negative dielectric response, like a noble metal.

- Silver is the preferred metal for this application because it has a significantly lower loss factor in the optical range compared to other metals.

Role of Surface Plasmons

- Similar to the perfect lens, the NFSL's super-resolution capability relies on surface plasmon polaritons at the interface between metal and host medium (e.g., silver and air).
- These surface modes are excited when the NFSL condition ($\varepsilon = -1$) is met.
- This specific frequency is often called the metal's surface plasmon frequency.
  - For silver, this corresponds to a wavelength of $\sim 340\ nm$, which is in the near-UV range.

Applications: While limited to the near-field zone, the NFSL has many interesting applications:
  - Includes biomedical imaging, sub-wavelength lithography and other near-field optical devices.

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Near-Field Superlens

Growth of evanescent waves and Superlensing effect using Ag slab

➢ **Experimental Evidence of Superlensing**

1. Silver-based NFSL (Optical/UV range):
   - Evanescent waves can be enhanced in a silver slab.
   - This enhancement continues until material loss becomes dominant.
   - An enhancement factor of over 30 using an optimized 50 nm thick silver film.
   - Berkeley experiment: (fig. (2))
     - ✓ Setup: Silver slab (35 nm ultra-flat film) sandwiched between photoresist layers.
     - ✓ Illumination: UV wavelength (365 nm).
     - ✓ Results:
       - ❑ This successfully captured images of a grating with a 60 nm half-pitch ($\lambda_0/6$) and a 40 nm line width, confirming sub-wavelength resolution.

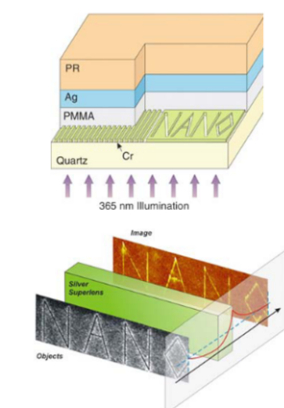

Fig. 2: Optical superlensing with a silver slab operating at a near-ultraviolet wavelength

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metamaterials are all dissipative. And they are lossy because of the plasmonic resonances. So, despite having the theoretical possibility of creating a perfect lens, making one in reality is extremely difficult. So, any real world losses or anisotropy or impedance mismatch in negative index materials which are kind of you know irresistible in the current designs ok, they all can eliminate the desired effect. So, that means the negative index materials created so far are all very lossy and highly dissipative.

And this is why there has been no far field demonstration of super resolution using planar negative index materials lab except for a few fundamental results which are demonstrated in the microwave range. So, let us look into some near-field superlenses. which is basically a simpler version of a perfect lens. So, we are talking about near field super lens because they can also achieve subweb length resolution. So, they are basically a simpler version of a perfect lens.

So, this design is easier to realize because it does not require negative permeability, which is optical magnetism. So, it only works with negative permittivity. So, how does it work? This near field superlens is basically based on quasi-static approximation which applies when all the system dimensions are basically sub-wavelength or smaller than the wavelength of the light that is involved. So, under this condition, the requirement for superlensing is for p-polarized or TM mode. waves can be simplified to the condition that you know the lengths is permittivity ε must be equal to the negative of the host mediums permittivity that is ε h.

So, you should have ε = - ε h ok. So, in that case, you know no optical magnetism is required. So, you can have a simplified version of the lengths compared to that of a full negative index material. So, here is an image of an optical superlensing that is achieved using a silver slab that is operating at ultraviolet wavelengths. So, these objects are having very tiny slits which are sub wavelength, but because of this silver superlense you can see the evanescent waves gets amplified and the information can be captured in the images right.

So, this is the schematic or the curtain that tells how it works, and this is exactly how it was. made okay. You have PMMA then silver and some photoresist then these are like the chromium slits ok and on a coarse substrate that is how it was made. Now, a couple of important things to remember here. So, when you are making a near-field superlens, the first important point will be the choice of the material.

Since you are focusing only on negative permittivity in the near field super length. So, it must be made from a material which has got a negative dielectric response such like such as noble metal right. So, you can choose silver for this application because it has significantly lower loss in the optical range as compared to other material like gold, copper and all. Now, there is a role for surface + bond. So, similar to the perfect lens here in the near field super lens the super resolution capability basically relies on the surface + bond polaritons at the interface between the metal and the host medium.

So, here it is: silver and air. So, this surface modes are basically excited when the condition for the near field superlensing will be met that is the permittivity of the silver will be equal to - 1 that is negative of the host here it is air ok. So, this specific frequency is often called the metal's surface + 1 frequency. Now, if you consider silver, this will correspond to a wavelength of 340 nanometers, which is typically in the near UV range, right? Now, what are the applications? So, while it is limited only to the near field zone, this near field superlensing has many interesting applications such as biomedical imaging, sub wavelength lithography and other near field optical devices. Now, if you come back to this particular design what we have seen earlier. So, what is happening here? The main factor that is working is the growth of evanescent waves, which is giving the superlensing effect because of this silver slab.

So, people have done experiments to provide evidence of superlensing. So, they have done this silver based ah near field superlensing in the optical or the UV range. So, here you can see that the evanescent waves are basically enhanced by the silver slab and this enhancement continues until the material loss becomes dominant. So, an enhancement factor of / 30 was recorded using an optimized 50 nanometer thick silver film ok.

So, this was the structure that was used. So, silver slab was having a thickness of say 35 nanometer which was sandwiched between this photoresist layers and they use 365 nanometer illumination wavelength which is in UV. And what was the result? They could capture images of gratings that you can see here with a$_{60}$-nanometer half pitch, which is typically λ naught / 6. And they can also record 40 nanometer line width okay from this structure that was confirming that they are able to capture the sub wavelength resolution. Now, people have also seen the growth of evanescent waves and the

Near-Field Superlens

Growth of evanescent waves and Superlensing effect using SiC slabs

- **Experimental Evidence of Superlensing**

  2. SiC-based NFSL (Mid-infrared range):
     - Uses **surface phonon polaritons** instead of plasmons.
     - This is possible because SiC's phonon-resonance property gives a negative permittivity.
     - Experimental Set-up: (fig.(3))
       - ✓ A 440 nm thick planar SiC slab used as a lens, sandwiched between two 220 nm thick silicon dioxide (SiO_2) films.
       - ✓ Best superlensing performance: at a wavelength of 10.8 μm, where the negative permittivity condition ($\mathrm{Re}(\epsilon_{SiC}) = -\mathrm{Re}(\epsilon_{SiO_2})$).
       - ✓ Resolution: A resolution of $\lambda_0/20$ achieved in this experiment by using a near-field scanning microscope to collect the image transferred through the SiC slab.

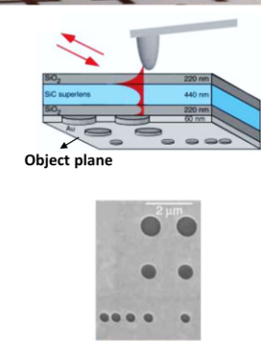

Fig. 3: Near-field superlensing with a SiC slab operating at MIR wavelength

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

superlensing effect using silicon carbide slabs. So, there were also people conducting experiments to see the superlensing.

So, this silicon carbide based near field superlensing was seen in mid infrared range So, it basically uses surface phonon polaritons instead of plasmons and this is possible because silicon carbides phonon resonance property basically gives a negative permittivity. So, again, you are using that negative permittivity, but the origin of that effect is not plasmon; here, it is basically the phonon resonance. So, this is the

Near-Field Superlens

Table-1: Comparison of Near-Field Superlenses (NFSLs)

Features	Silver NFSL	SiC NFSL
Mechanism	Surface plasmon polaritons	Surface phonon polaritons
Wavelength range	UV (365 nm)	Mid-IR ($10.8\ \mu m$)
Lens material	Silver (Ag) slab	Silicon carbide (SiC) slab
Lens thickness	$35-50$ nm	440 nm
Supporting layers	Photoresist layers	SiO_2 thin films (220 nm each)
Evanescent wave amplification	Enhancement factor > 30 (optimized thickness)	Achieved by phonon resonance
Resolution achieved	60 nm half-pitch ($\lambda_0/6$) and 40 nm linewidth	$\lambda_0/20$
Experimental method	Near-field optical lithography	Near-field scanning microscopy
Key advantage & Applications	Works in optical regime (UV imaging, nanolithography)	Works in IR regime (thermal/biological imaging)

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

experimental setup, as you can see. A 440 nanometer thick planar silicon carbide slab was used as a lens which is sandwiched between two 220 nanometer thick silicon dioxide films here and here and then you have this object plane. So, this is the SEM image of the object plane that is being used, and this is the probe, okay.

So, the best superlensing performance was obtained at a wavelength of 10.8 micrometer where basically you are getting that negative

"Tunable" Superlens using Random Composites

Limitations of Silver NFSL:

- A silver NFSL operates only at a single frequency, where lens condition $\varepsilon(\omega) = -\varepsilon_h$ is satisfied.
- For silver slab in air, this condition occurs at ~ 340 nm (UV).
- Difficult to extend to other wavelengths, especially beyond visible range, due to mismatch with realistic host materials.
- To satisfy the lens condition in the visible range, the host medium would need an extremely large permittivity (high-index dielectric).
  However, realistic materials with such large ε_h do not exist (or suffer strong absorption).

Solution via Metal–Dielectric Composites

- Using a metal-dielectric composite as the lens material offers a significant advantage.
- Composite films have an effective permittivity (ε_e) depends on the permittivities and filling factors of both the metal and dielectric components.
- This added flexibility allows the condition: Re(ε_e) $= -\varepsilon_h$ at different wavelengths.
- Enables **tunable NFSL** operation across visible and near-IR ranges.

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

"Tunable" Superlens using Random Composites

- **Schematic Concept: (Shown in Fig. 4)**
  - A metal-dielectric composite slab acts as a flexible alternative to bulk metal slabs.
  - Provides a practical path to multi-wavelength or tunable superlensing.
  - The optical properties of metal-dielectric composites are well described by the effective medium theory (EMT).
  - According to the EMT, the composite material can be treated as a single homogeneous medium with an **effective permittivity** (ε_e).
  - This effective permittivity is a function of the permittivities of the constituent materials, their volume filling factors, and the dimensionality of the composite.

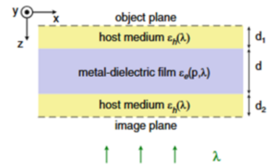

Fig. 4: Schematic of the tunable NFSL based on a metal-dielectric composite

$$\varepsilon_e = \varepsilon_e' + i\varepsilon_e'' = \frac{1}{2(\mathrm{d}-1)}\Big\{(dp-1)\varepsilon_m + (\mathrm{d}-1-dp)\varepsilon_\mathrm{d} \pm\sqrt{\left[(dp-1)\varepsilon_m + (\mathrm{d}-1-dp)\varepsilon_\mathrm{d}\right]^2 + 4(\mathrm{d}-1)\varepsilon_m\varepsilon_\mathrm{d}}\Big\}$$

where the sign should be chosen such that $\varepsilon_e'' > 0$.

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

permittivity condition that is the real part of the permittivity of the silicon carbide was equal to the negative of the real part of the silicon dioxide permittivity. So, what was the result? A resolution of λ naught by 20 was achieved in this experiment which was obtained using a near field scanning microscopy that could collect the image transferred through this silicon carbide slab. So, here is a table that compares the two near-field superlenses. So, one is based on silver; another is based on silicon carbide.

So, the mechanism is different; the first one works on surface + one polariton, while the other one works on surface phonon polaritons. Here you can see the wavelength range this one works for: UV 365 nanometers; the other one is for mid IR, which is 10.8 micrometers. The lens material, here it is silver slab and here it is silicon carbide slab. The thickness of the lens was 35 to 50 nanometers, whereas now it is 440 nanometers.

The supporting layers were a photoresist layer and a silicon dioxide thin film, each with a thickness of 220 nanometers. Here, the evanescent wave amplification was more than 30. Mainly, it was done because of the surface + one polariton or surface + one resonance. Here it was from phonon resonance and resolution achieved here was λ naught by 6 and here you can see you can go up to λ naught by 20. So, experimental method here it was used near field optical lithography and here we they used near field scanning microscopy.

So, what is the key advantage? So, it basically works in the optical regime. So, UV imaging or nano lithography can be

"Tunable" Superlens using Random Composites

- **Effective permittivity formula:**

$$\varepsilon_e = \varepsilon_e' + i\varepsilon_e'' = \frac{1}{2(\mathrm{d}-1)}\Big\{(\mathrm{dp}-1)\varepsilon_m + (\mathrm{d}-1-\mathrm{dp})\varepsilon_\mathrm{d} \pm\sqrt{\big[(\mathrm{dp}-1)\varepsilon_m + (\mathrm{d}-1-\mathrm{dp})\varepsilon_\mathrm{d}\big]^2 + 4(\mathrm{d}-1)\varepsilon_m\varepsilon_\mathrm{d}}\Big\}$$

In fig. (4), d-dimensional composite material comprising metal particles with permittivity ε_m and a volume filling factor p, along with a dielectric component with permittivity ε_d and a filling factor $(1-\mathrm{p})$.

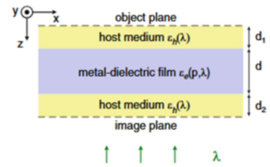

Fig. 4: Schematic of the tunable NFSL based on a metal-dielectric composite

- **Key Mechanism for Tunable NFSL**
  - The ability to tune a near-field superlens depends on the relationship between its ε_e, light wavelength (λ), and metal filling factor (p).
  - Operational wavelength (λ_{op}) satisfies condition for superlensing: $\mathrm{Re}\big[\varepsilon_e(\mathrm{p},\lambda_{op})\big] = -\varepsilon_h(\lambda_{op})$.
  - Tuning achieved by varying metal filling factor (p) → ε_e changes.
  - Enables broad operational wavelength (λ_{op}) control for NFSL applications.

applications, and silicon carbide works in IR. So, you can use it for thermal or bioimaging applications, right? So, let us discuss what the limitations of the silver near-field superlens are. You can see that a silver near-field superlens basically operates at a single frequency where the lens condition, which is that the

Principle of Tunable NFSL Operation

Principle of tunable NFSL operation: illustrated in fig. 5.

- **Example: Tunable NFSL operation** with silver-silicon dioxide ($Ag{-}SiO_2$) composite film:
  - Material Basis:
    - ❑ Permittivity of Silver (Ag) described by Drude model.
    - ❑ Composite film: $Ag{-}SiO_2$ with metal filling factor $\mathrm{p} = 0.85$.
    - ❑ Effective permittivity (ε_e) calculated via 2D EMT model.(fig. 5)
  - Effective Permittivity Behavior for composite film:
    - ❑ Real part of ε_e: smaller magnitude than pure Ag.
    - ❑ Imaginary part of ε_e: broad surface-plasmon absorption band (due to grain interactions).
  - Pure Silver Slab Operation:
    - ❑ For a pure silver slab, the superlensing condition: $\mathrm{Re}\big[\varepsilon_e(\mathrm{p},\lambda_{op})\big] = -\varepsilon_h(\lambda_{op})$, is met at a single wavelength (λ_{op}).
    - ❑ This is marked in the figure by points A, B, and C for host media of air, silicon carbide (SiC), and silicon (Si) respectively.

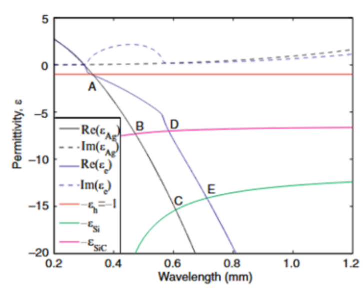

Fig. 5: Principle of NFSL operation

Principle of Tunable NFSL Operation

- Using a composite Ag–SiO_2 film allows for greater tunability and avoids significant losses.
- **Advantage of Using Semiconductor Hosts (Si, SiC)**
  - Semiconductors like Si and SiC, which have a large permittivity (ε_h), are beneficial as host media.
  - High permittivity (ε_h) → shifts λ_{op} outside plasmon absorption band.
  - Benefit: avoids large losses from high Im(ε_e), improves resolution.
  - Imaginary parts of permittivities of Si & SiC in visible-NIR range ≈ negligible → minimal additional losses.
- Composite NFSL Operation (shown in fig. 5)
  - With p = 0.85 :
    - ❑ Point D (SiC host)
    - ❑ Point E (Si host)

    Both outside absorption band → efficient NFSL operation.

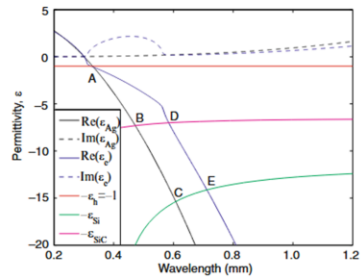

Fig. 5: Principle of NFSL operation

- Conclusion: By selecting a suitable host material and adjusting metal filling factor (p),
  - A composite metal-dielectric NFSL can be designed to operate at any desired wavelength within a wide visible-NIR range.

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

permittivity of the silver will be equal to - the permittivity of the host, is satisfied. Now for silver slab in air the condition was satisfied at 340 nanometer which is in UV.

Now it is very difficult to extend this wavelength, especially beyond the visible range, due to, you know, a mismatch with realistic host materials. Now, to satisfy the lens condition in the visible range. The host medium needs to have extremely large permittivity. So, you require a high index dielectric. But you know in reality this kind of material do not exist which has got very large permittivity or basically they suffer from very strong absorption.

So, that is the practical limitation of making this superlens beyond the visible range. Now the solution here comes from, you know, instead of using silver, you go for metal dielectric composites. okay so if you can use metal dielectric composite as a lens material that offers significant advantage okay so the composite films can have effective permittivity that is ε e which depends on the permittivities and the filling factors of both metal and dielectric components Right. So, this added flexibility, so you can actually change the volume fraction and tune the permittivity and this flexibility allows you to you know satisfy this equation ok at different wavelengths and that basically gives you tunable near field superlensing operation across visible and near infrared ranges. so a schematic concept is shown here in this particular figure so you can see a metal dielectric composite slab basically acts as an alternative to the bulk metal slab so you can consider the thickness to be d here and you have host medium d_1 and d_2 on the two sides so this provides a practical path to multi-web length or you can say tunable superlensing So, the optical properties of this metal-dielectric composite can be described using effective medium theory, which we have discussed earlier.

So, you can basically treat this composite as a homogeneous medium that has a permittivity ε e. Now, how you can obtain this permittivity ε e that basically depends on the metal and the dielectric permittivity and also the volume fraction ok. So, we can see in detail how you get this.

So, the d dimensional composite material that comprises of metallic particles which have got permittivity ε m and volume fraction is p. and that way you understand that the dielectric component will have permittivity ε d and the volume fraction will be 1 - p.

So, this formula basically gives you an estimate of the effective permittivity that can replace the solid metallic slab. Now, the ability to tune a near field super lens imaging or super lens depends on this relationship between this ε e, the light wavelength λ and the metal filling fraction. So, you can find your operational wavelength that would basically satisfy this superlensing condition. That is you have to find the real part of this effective permittivity for a desired or tunable volume fraction at the desired operational frequency and that should be equal to the - of the host at that operational wavelength. So, what you are achieving here is that you can change the metal filling factor and you can change ε E and that will allow you to satisfy this.

So, you basically get broad operational wavelength control for near-field superlensing applications using this method. So, this principle is also shown here, okay. So, you can consider a silver-silicon dioxide composite film. So, you can say it is a silver silicon dioxide composite film. So, you can describe this using a Drude model and if you consider the composite film with a metal filling fraction of P = 0.

85, you can compute the effective permittivity which is basically shown here ok. So, this tells about the effective permittivity behavior of the composite film. So, for a pure silver slab, you are basically getting this superlensing of condition met at a particular wavelength, but here you can see that all these different points are marked. So, A, B, and C are basically the permittivity of the host of air, silicon carbide, and silicon, okay. Using a composite film that basically gives you greater tunability and allows you to avoid significant losses.

So, the solid lines here are basically the real part of the permittivities, and the dotted lines basically show you the losses, okay. So, what are the advantages of using a semiconductor host here, silicon or silicon carbide? They basically have a large permittivity. So, they are good for the host medium. And when you have large permittivity that allows you to shift the operational wavelength outside the plasmon absorption band. So, you can avoid even large losses that are coming from the large or high imaginary permittivity, which improves the resolution.

So, finally, you can see that the imaginary part of the permittivity allows you to have minimal additional losses. So, these are the other two points marked for P = 0.85. So, this is for the silicon carbide host, and this is for the silicon host.

So, both of you can see they are outside the absorption band. So, they basically allow efficient NFSL operation. So, here is the conclusion that by selecting suitable host material. and adjusting the metal filling fraction p, you can make a composite metal dielectric near field superlens that can operate at any desired wavelength within the wide visible near infrared range.

So, with that, we conclude here. Thank you for your attention. If you have got any query, please drop an email to this email address mentioning the course name and the lecture number on the subject line. Thank you.

Slides inserted by fallback (review if needed):