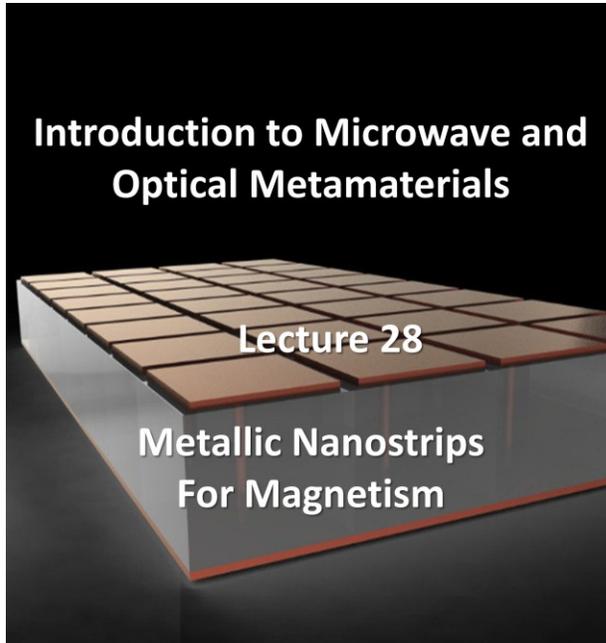


**Course Name: Introduction to Microwave and Optical Metamaterials**  
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**Week-6**  
**Lecture-28**

Lec 28: Analytical model of magnetic nanostrips



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## Lecture Outline

- Pair of Metal Strips as Magnetic Metamaterial
- Magnetism in the Visible Spectrum
- Analytical model of magnetic nanostrips

Hello everyone, welcome to Lecture 28 of the online course on Interaction with Microwave and Optical

## Pair of Metal Strips as Magnetic Metamaterial

- The nanostrip magnetic metamaterial is made of a pair of metallic nanostrips separated by a dielectric layer.
- The upper and lower strips are non-identical – overall cross-section of the strip pair is trapezoidal in shape.
- Under TM illumination, the nanostrips show both magnetic and electric resonances (with magnetic field along the strips).
- Under TE polarization, with the electric field along the strips, no resonance occurs.
- Fabrication is achieved using electron-beam lithography and vacuum deposition.

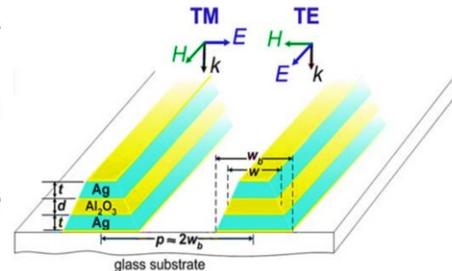


Fig. Schematic of the structure consisting of coupled nanostrips.

## Pair of Metal Strips as Magnetic Metamaterial

- Figure – Field-emission scanning electron microscope (FE-SEM) and atomic force microscope (AFM) images of the structure.
- Transmission, reflection, and absorption spectra confirm resonance peaks at specific wavelengths (denoted  $\lambda_m$  for magnetic and  $\lambda_e$  for electric).
- Simulations using COMSOL Multiphysics® illustrate the field distribution at magnetic ( $\lambda_m$ ) and electric ( $\lambda_e$ ) resonance wavelengths.
- A cross-section of the Ag–Al<sub>2</sub>O<sub>3</sub>–Ag nanostrip structure is shown with:
  - Arrows indicating electric displacement
  - Color map representing magnetic field intensity

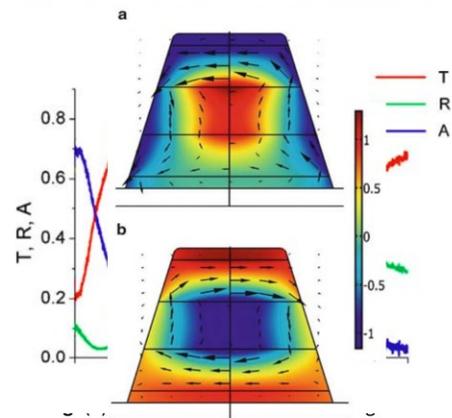


Fig. 5. Simulated electric displacement and magnetic field distributions at (a) the electric resonance  $\lambda_e$  and (b) the magnetic resonance  $\lambda_m$

## Pair of Metal Strips as Magnetic Metamaterial

- At magnetic resonance ( $\lambda_m$ ):
  - Electric displacement loops, creating an artificial magnetic moment
  - A strong magnetic field appears between the metal strips
- At electric resonance ( $\lambda_e$ ):
  - Electric displacement is mostly linear, with a minor circulating component
  - The magnetic field is weaker, and the minor loop (arrows) in displacement yields a magnetic anti-resonance

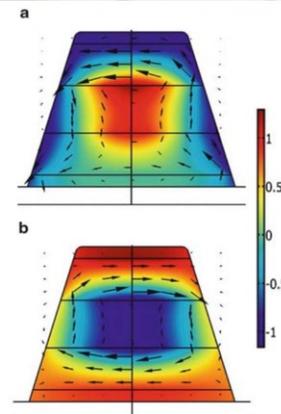


Fig. 6. Simulated electric displacement and magnetic field distributions at (a) the electric resonance  $\lambda_e$  and (b) the magnetic resonance  $\lambda_m$

Metamaterials. In today's lecture, we will continue our discussion on metallic

## Magnetism in the Visible Spectrum

- Early metamaterials: Relied on SRRs and similar structures as the primary magnetic “meta-atoms”.
- Magnetic range: Covered from C-band microwave frequencies to 800 nm wavelength.
- Visible wavelength limitation:
  - SRRs face scaling constraints, limiting their use in visible light applications
  - Alternative structures like coupled nanorods or nanostrips are more effective
- New approach:
  - Utilizes arrays of paired thin silver strips
  - Enables strong, tunable magnetic responses in the visible spectrum

nanostrips for magnetism. So, here is the lecture outline, we will continue the discussion on the pair of metallic strips as magnetic metamaterials that you have seen towards the end of the last lecture. We will see how we can have magnetism in the visible spectrum and then we will develop an analytical model for those magnetic nanostrips that give us better idea of what we are doing. So, if you recall from the previous lecture, the basic structure of the nanostrip magnetic metamaterial basically consists of a pair of metallic strips here you can see the two which is spaced by a dielectric layer here we are using alumina okay  $Al_2O_3$ . Now the upper and lower strips are not identical, and that is why the overall cross section of the strip pair will look trapezoidal in shape.

Now the nanostrip structure exhibits both magnetic and electric resonances under TM polarization, where you see the magnetic field is basically polarized along the strip, right? Under T polarization, the electric field is basically polarized along the strip. The structure shows no resonance effects. And we have seen that the fabrication of this can be achieved through electron beam lithography and vacuum deposition. So, here the figure shows the field emission scanning electron microscope that is FESAM ok, image and this is atomic force microscopy image of the fabricated structure of this paired nanostrips ok.

Now, in this structure, when you calculate or characterize them and obtain the experimentally measured values of transmission, reflection, and absorption, which are plotted here, okay. So, this is absorption, okay. This is reflection, and this is the transmission, okay. What you basically see here that all done under TM polarization because that is where you can excite those magnetic and electric resonances and the resonances are marked as  $\lambda_m$  and  $\lambda_e$ . Now, if you want to understand the nature of this magnetic and electric resonances, it is also good to do simulations of the electromagnetic field using commercial software something like COMSOL multiphysics, okay.

That will allow you to see the field distribution at these two resonance wavelengths.  $\lambda_m$  and  $\lambda_e$

are okay, and this is how they look. So, here is basically the cross sectional view of this paired nanostrip and the top one shows the electric resonance, the distribution of the electric displacement field at  $\lambda_e$ . Here you see the magnetic field distribution at the magnetic resonance wavelength of  $\lambda_m$ .

Ok. So, you can clearly see that these particular arrows show the electric displacement and the color map shows the magnetic field, right? So, the arrows are basically indicating the electric displacement, and the color map gives you the magnetic field intensity, which is something important to remember, right? Now, let us take them one by one. So, in this particular case of B, where you are seeing the magnetic resonance, you can see that the electric displacement is predominantly aligned along one direction, right? So, we are talking about this one, right? So, at the magnetic resonance at  $\lambda_m$ , which is in figure b, you can see that the electric displacement is basically forming a loop. So, there is a loop of the electric displacement current, and that results in an artificial magnetic moment, right? So, you will also see a strong magnetic field inside the loop between the two metal strips. Now, if you go to the upper figure that corresponds to the electric resonance at the  $\lambda_e$  wavelength. So, there you see that the electric displacement is predominantly aligned along only one direction, with small circulating components.

That means the magnetic field is much lower compared to the magnetic resonance present here. The small circulating component of this electric displacement basically gives you a small magnetic moment. However, this is much weaker. And another important thing is to see that the minor loops that you can see from the arrows in the displacement basically give you magnetic anti resonance. Now, during the first few years of the intense study of this kind of

## Magnetism in the Visible Spectrum

- Different metals have been used to create functional units of metamaterials.
- Material selection by frequency:
  - Microwave: Copper is favored, especially for PCB-based metamaterials
  - Infrared: Gold and silver are common; gold is preferred for its stability and fabrication compatibility
- Visible frequency challenges:
  - Silver is ideal due to its smaller loss factor (better than gold)
  - Gold is less suitable due to:
    - ✓ Higher losses (about  $3 \times$  that of silver)
    - ✓ Absorption edge falls within visible light due to interband transition ( $5d \rightarrow 6sp$ )
- Therefore in magnetic nanostrips operating in the visible range, silver is chosen to form the pairs of metal strips.

## Magnetism in the Visible Spectrum

- Dielectric spacer considerations:
  - Use high dielectric constant materials to enhance field confinement
  - Alumina ( $n > 1.6$ ) is preferred over silica ( $n < 1.5$ )
  - Silicon and germanium are avoided due to losses from bandgap transitions
- Structure: Nanostrip pair stack has a trapezoidal shape.
- Layer thicknesses:
  - Silver layer:  $t = 35$  nm
  - Alumina spacer:  $d = 40$  nm

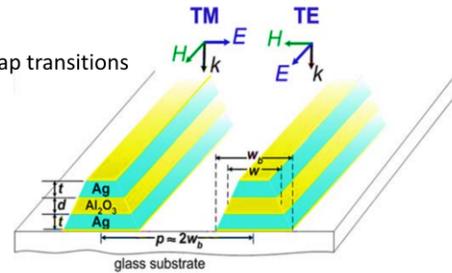


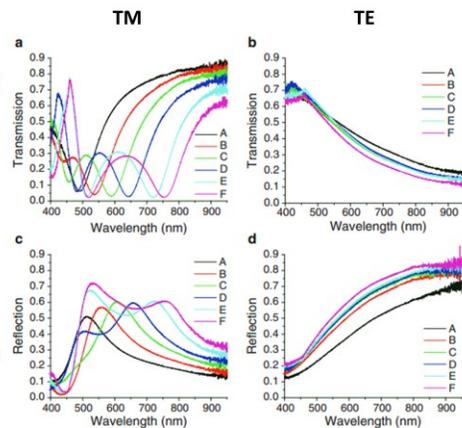
Fig. Schematic of the structure consisting of coupled nanostrips.

- Six different structures with varying widths were prepared on the same substrate and were fabricated simultaneously for a fair comparison.

metamaterials, splitting resonators and their analogues have been the meta atom of choice for this kind of magnetic

## Magnetism in the Visible Spectrum

- Sample Range:
  - Strip widths from 50 nm (Sample A) to 127 nm (Sample F)
- Measurement Focus: Transmission and reflection spectra reveal resonance behavior.
- TM Polarization: Strong resonances observed (Fig. a, c).
- TE Polarization:
  - Non-resonant wavelength dependence over a broad range
  - Samples acts like a diluted metal
  - Explains the blue transmission (Fig. b) and red reflection (Fig. d)



metamaterials.

Their magnetic response usually spanned / C band microwave frequencies to even you know the end of the long wavelength end of the visible spectrum right. Now at a visible wavelength that is between 800 nanometers and 400 nanometers. Other structures, like coupled nanorods or nanostrips, were basically preferred. Splitting resonators could not go beyond that because of the

saturation effect, which we have already discussed in the previous lecture, as this has its intrinsic limit. So, these couple of nanorods and nanostrips became popular.

So, in this particular lecture we will see a route to strong and controllable magnetic response in the visible wavelength range mainly using structures like you know paired of thin silver strips ok that can give a strong tunable magnetic response within the visible spectrum. Now before we proceed with discussing experimental demonstration of magnetism in the visible range, it is important to address one issue that is regarding the constituent materials which are typically used in metal dielectric metamaterials that operates within the visible range, right. So, for metamaterials that are operational from microwave frequencies okay to near infrared okay, but you know in the case of micro frequencies copper is the commonly used one specifically for PCB based metamaterials because they are easy to fabricate as well okay using the PCB fabrication. However, for the infrared band of the optical frequencies both gold and silver structures are routinely used of which you know gold is typically preferred going to better performance in various nanofabrication techniques and also it is more stable against you know experiment environmental degradation such as oxidation and all. So, what are the challenges in the visible frequency range? So, if you want to design metamaterials at visible frequencies, silver is ideal due to its smaller loss factor compared to gold.

As we discussed that although gold is more stable, gold is found to be less suitable in terms of performance because it has got higher losses typically 3 \* larger losses as compared to silver. Moreover, the absorption edge of gold due to the interband transition from 5D to 6SP falls within the visible range which essentially rules it out as a material of choice for metamaterials at the visible range. Frequencies. Therefore, whenever people tried you know making metallic nanostrips which are supposed to operate in the visible range, silver was the choice of material to form the pair of metal strips. Now, as for the dielectric spacer between the silver nanostrips ok, you have to choose a material with relatively large dielectric constant that can give you better field confinement right.

So, in the present structure as you can see alumina which has got a refractive index more preferred / silica which has got a refractive index less than 1.5. And also note that you know semiconductors with high dielectric constants such as silicon and germanium should not be used for visible light

## Magnetism in the Visible Spectrum

- Magnetic resonances span 491–754 nm, covering most of the visible spectrum.
- Resonance Shift:
  - Resonance wavelengths shift towards blue as strip width ↓
  - Confirms consistent magnetic resonance scaling behavior
- Spectra Overview (TM polarization, Sample E) Three characteristic wavelengths analyzed.
- Magnetic Resonance ( $\lambda_m$ ):
  - Caused by anti-symmetric current flow in paired strips
  - Forms circular current → magnetic dipole response
  - Key resonance to pursue in nanostrip designs

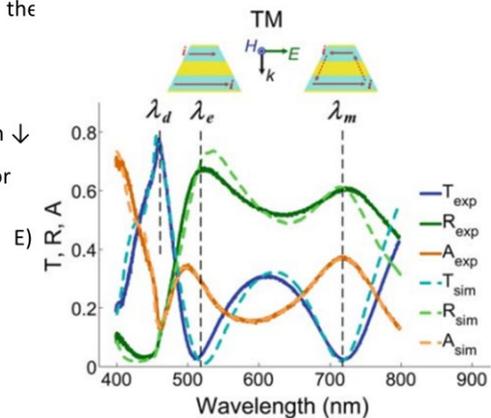


Fig. Transmission (T) and reflection (R) and absorption (A, including diffractive scattering) spectra under TM polarization.

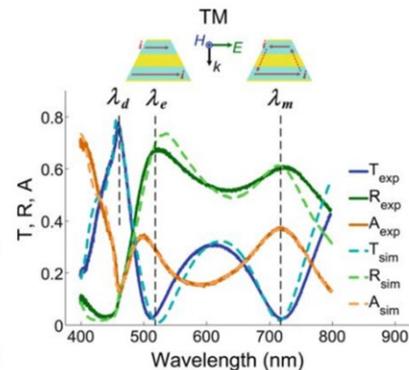
metamaterials because of the substantial loss caused by electron transition across the band gap okay. So, now we move on to the discussion of the experimental demonstration of magnetism in the visible frequency range using a nanostrip.

Pair samples. So, again these are gold sorry silver nanostrips separated by alumina and we have seen this structure already this nanostrip pair stack has a trapezoidal cross section and these are the other dimensions you have got a the silver layer thickness is 35 nanometer The spacer has a thickness of 40 nanometers, and then people have fabricated 6 different structures with varying widths. So,  $W$  has been changed on the same substrate and fabricated simultaneously for a fair composition. So, the 6 samples are basically named here A to F. They have strip widths starting from 50 nanometers to 127 nanometers. So, A is the thinnest one and F is the widest one, okay.

The

## Magnetism in the Visible Spectrum

- Electric Resonance ( $\lambda_e$ ):
  - Caused by symmetric current flow
  - Results in an electric dipole effect
- Spectral Effects:
  - Transmission: Two local minima at  $\lambda_m$  and  $\lambda_e$
  - Reflection: Two local maxima at  $\lambda_m$  and  $\lambda_e$
  - Absorption: Enhanced near  $\lambda_m$  and  $\lambda_e$  which is natural for plasmonic resonances in metal-dielectric structures
- Diffraction Threshold ( $\lambda_d$ ): This characteristic wavelength indicates the diffraction threshold and acts as a fingerprint for grating-like structures.



**Fig.** Transmission (T) and reflection (R) and absorption (A, including diffractive scattering) spectra under TM polarization.

transmission and reflection spectrum; this row is transmission, this row is reflection, the left column is for TM polarization, and the right column is for TE polarization. So, this transmission and reflection spectrum of all the samples were measured to reveal the nature of the resonance qualitatively, right. So, what you can see that for the TM polarization, okay you can see strong resonances getting observed whereas for the T polarization there is no resonance so you are basically seeing non-resonant wavelength dependence / broad range and The slopes okay of the spectra in the T mode basically tells you that the samples basically act like diluted metal in this case and that could explain that the samples will look blue because you are having so much transmission in the blue regime. So, it will look blue in the transmission mode and in the reflection mode they will look like you know red okay. So that you can observe from here.

Now, the magnetic resonances that you can see in the TM polarization case basically occur / a span of 491 to 754. So, typically from this graph, you can see the resonance. So, that basically covers most of the visible spectrum, which is very good. And it is important to note the position of the resonant wavelength in this TM mode and you can see that they basically move towards blue when decreasing the width of the strips from sample F.

To sample a right. So, this basically confirms consistent magnetic resonance scaling property which is a good indication and that can serve as a guideline to develop other devices or meta atoms for this kind of magnetic responses within the visible range. The spectra for TM polarization, so if you look into it more carefully, okay. So, the spectra for the TM polarization is shown here; it has basically three distinctive characteristic features, okay. So, you can actually see that there is. magnetic resonance which is  $\lambda_m$ .

So, again these three colors basically tell you about the blue is the transmission, the green is the absorption in this case and this red is the reflectance. The dashed ones are basically simulation, the solid ones are basically experiment So, what you are doing we just took one particular set

from the previous slide and we want to go into details and understand what are these peaks what they represent. So, you can see that for TM polarization, you are observing magnetic resonance. So, you are taking the spectra from TM polarization; you identify these peaks. What is happening here? So, you can see that you do know.

The magnetic resonance basically shows that it is caused by an anti-symmetric current flow in the paired strips. You can see at the bottom strip that the current is flowing this way, and in the upper strip, it is flowing in the opposite direction. So, you basically have a loop forming, and that is giving you the magnetic resonance, okay. And this key resonance is very important for pursuing the nanostrip designs. Now, if you look into the second feature which is the electric resonance that is basically caused by a symmetric current mode you can see in this case the currents are basically in the same direction ok.

So, this electric resonance is coming from symmetric current flow, and it gives you an overall electric dipole effect, okay. so the spectral characteristics are like you know these two resonances basically give you a local minima in the transmission spectrum okay and they are appearing as maxima on the reflection spectrum right the absorption spectrum which is here okay. That also shows that the absorption is getting enhanced when you are close to these two resonance wavelengths, and this is natural for plasmonic resonances in metal-dielectric structures. Here, the materials are plasmonic because you are using silver, and you can actually see them. So, once again to summarize what you are seeing, you are seeing in the transmission are basically seeing two dips 1 at  $\lambda_m$ , 1 at  $\lambda_e$ .

In the reflection you are seeing two maximum local maxima 1 at  $\lambda_m$  and  $\lambda_e$  and then the absorption is also seen to get enhanced near those because this is from the plasmonic resonance. Now, if you follow the transmission spectra the blue one, it also displays a sharp know turn back at relatively short wavelength which is marked as you know  $\lambda_d$ . So, this characteristic wavelength basically indicates the diffraction threshold and serves as a fingerprint for such grating like structure. So, from here, it will behave like a diffraction grating, okay. So, for practical designs and application it is desirable to have an analytical expression for the relation between the magnetic resonance wavelength  $\lambda_m$  and the geometric parameters such as W, D and T of this paired strip structure.

Now, following the cavity model approach that we have discussed, okay, we see that for the range of parameters used in the experiments shown above, where you know you have  $\lambda_m$  greater than  $2ndw$ , okay, the resonance can be described by this okay. So, you can write  $\epsilon_m$  prime at  $\lambda_m$ ;  $\epsilon_m$  prime is basically the real part of the metal permittivity, okay. And  $N_d$  is basically the refractive index of the dielectric spacer, and the equation looks like this. So, you have  $\epsilon_m$  prime  $\lambda_d = 1 - N_d^2 / T \kappa^2 * 1 + \cot H d \kappa$  by 2, where kappa can be written as square root of  $\pi/W$  whole square -  $2 \pi N D / \lambda_m$  whole square, right. Now, because the fabricated structure is indeed more complicated than this kind of ideal case that is described in the cavity model.

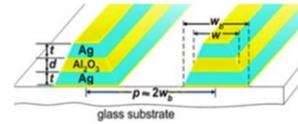
There are small deviations from the  $\lambda_m$  that is calculated and the ones that are experimentally

measured, right. And if you introduce, you know, some kind of effective width, such deviations can be completely accounted for, okay. So, you have to introduce a new concept called the effective strip width. So, you can call  $W$  effective okay. So, for the range of parameters which are used in the experiments calculation shows that you know  $W$  effective is typically slightly smaller than the bottom width of the strip okay.

So, you can consider  $W$  effective to be  $0.96 * W_b$ . Okay. And that improves the accuracy of the simulation compared to the

## Analytical Model of Magnetic Nanostrips

- Analytical relation between magnetic resonance wavelength ( $\lambda_m$ ) and geometric parameters ( $w, d, t$ ) is derived for paired-strip structures.
- Using a cavity model approach, valid when  $\lambda_m > 2n_d w$ , the resonance is described by:



$$\epsilon'_m(\lambda_m) = 1 - \frac{n_d^2}{t\kappa} \left[ 1 + \coth\left(\frac{d\kappa}{2}\right) \right], \kappa = \sqrt{(\pi/w)^2 - (2\pi n_d/\lambda_m)^2}$$

where  $\epsilon'_m$  is the real part of the metal permittivity and  $n_d$  is the refractive index of the spacer

- Due to fabrication complexity, experimental values deviate slightly from this model.
- Introducing an effective width  $w_{\text{eff}} = 0.96w_b$  (bottom width) improves accuracy.

experimental results. Now, the equation basically lacks an

## Analytical Model of Magnetic Nanostrips

- The equation lacks exact analytical solution but allows useful approximations.

- By applying first-order approximations:

- Hyperbolic cotangent simplification when  $d\kappa/2 \ll 1$
- Neglecting the second term under square root assuming  $2n_d w \ll \lambda_m$

- Silver's permittivity  $\epsilon'_m$  is modeled by the Drude model as:

$$\epsilon'_m(\lambda) = 5 - \lambda^2/\lambda_p^2$$

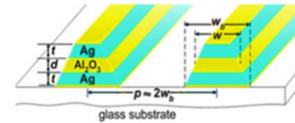
where  $\lambda_p = 134.6$  nm

- The approximated resonance wavelength ( $\lambda_m$ ) is given as:

$$\lambda_m = \sqrt{4 + \frac{n_d^2 w}{\pi t} + \frac{2n_d^2 w^2}{\pi^2 t d}} \lambda_p$$

$$\epsilon'_m(\lambda_m) = 1 - \frac{n_d^2}{t\kappa} \left[ 1 + \coth\left(\frac{d\kappa}{2}\right) \right]$$

$$\kappa = \sqrt{(\pi/w)^2 - (2\pi n_d/\lambda_m)^2}$$



## Analytical Model of Magnetic Nanostrips

- Physical insights from the approximation:

- Narrower strip width ( $w$ )  $\rightarrow$  shorter  $\lambda_m$
- Thinner metal thickness ( $t$ )  $\rightarrow$  red-shift in  $\lambda_m$

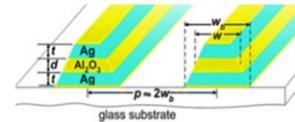
- Alternative approximation for the equation is applicable when:

$$(w^2 \gg \lambda_p^2 \text{ and } td \gg \lambda_p^2) \text{ while } d\kappa/2 \ll 1$$

- In this limit, resonance wavelength  $\lambda_m$  becomes:

$$\lambda_m \approx 2n_d w (1 + \lambda_p^2/4\pi^2 td) \approx 2n_d w$$

$$\lambda_m = \sqrt{4 + \frac{n_d^2 w}{\pi t} + \frac{2n_d^2 w^2}{\pi^2 t d}} \lambda_p$$



analytical solution, but it gives useful approximations in some cases, right? So, the first order approximation for the hyperbolic cotangent function with this parameter  $d\kappa/2$ , much less than 1, can be incorporated to simplify this expression.

In addition the second term in the square root okay can be also neglected assuming that this is much much smaller as compared to  $\lambda_m$ . So, if you do this approximation the permittivity of silver that is  $\epsilon'_m$  can be modeled by Drude model only and you can write  $\epsilon'_m$  The

function of  $\lambda$  will be  $5 - \lambda$  squared by  $\lambda p$  squared, where  $\lambda p$  squared is 134.6 nanometers, which is basically the plasma wavelength of silver. Now, in that case using this kind of simplification the approximate solution can be written as  $\lambda_m$  which is square root of  $4 + n$  square  $w / \pi t + 2 n$  square  $w$  square /  $\pi$  square  $t d * \lambda p$ . So, you see the magnetic resonance is basically function of this dielectric spacer refractive index, width of the strip  $w$ ,  $t$  that is appearing  $w$ ,  $w$  is the average width right.

yeah  $W$  is the width you can say width of the strip and then you have the thickness and you have the dielectric spacer thickness and  $\lambda p$  which is the plasma wavelength of silver. Now this approximation provides some physical insight and confirms the intuitive conclusion that scaling down the width of the strip will result in a shorter resonant wavelength  $\lambda_m$ , right. So, that is the first thing that you can see. Next, there is a less intuitive conclusion that involves reducing the thickness  $t$ . Okay, the metallic strips will tend to give  $\lambda_m$  a redshift.

So, if you choose a thinner metallic thickness, you will get a redshift in  $\lambda_m$ , which is observed in both simulations and theory. Another interesting observation is that an approximation can be obtained. The dimensions of the couple strips are relatively large that is if you can consider  $W$  square to be much much larger than  $\lambda p$  square and  $Td$  to be much much larger than  $\lambda p$  square in that case you know.  $d$  kappa by 2 will be much smaller than one. So, in this particular limit the resonance wavelength  $\lambda_m$  will become approximately equal to  $2 n_d w * 1 + \lambda$  square  $\pi_4 \pi$  square  $Td$  which can be approximated as this okay because this is also small.

So, you can consider this as only  $2n_d w$ , right? So, in this kind case or in this kind of approximation, the resonant wavelength is basically

## Analytical Model of Magnetic Nanostrips

- Key implications:
  - $\lambda_m$  becomes independent of metal thickness  $t$  and separation  $d$
  - Resonant wavelength depends only on the geometric width  $w$
  - Accurately models microwave magnetic media using paired metal wires
  - Reflects the basic mode of an electromagnetic cavity with size  $w$
- Figure shows how the magnetic resonance wavelength  $\lambda_m$  varies with average strip width  $w$  for trapezoidal-shaped paired-strip samples.
- Experimental results and analytical calculations using the equation with  $w_{\text{eff}} = 0.96w_b$  are compared.

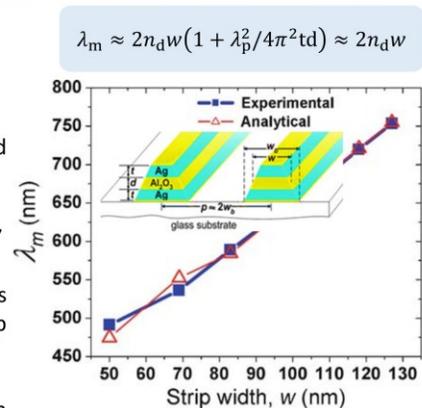


Fig.  $\lambda_m$  vs average width  $w$  of the trapezoidal-shaped paired-strip samples.

independent as you can see of the thickness  $t$  and the separation  $d$ , right. And it is only depending on the geometric parameter  $W$ . So, this limiting case basically accurately describes a microwave

magnetic media using paired metallic wires where the resonant wavelength is solely dependent on the length of the wires. So, not surprisingly the second approximation leads to a natural solution of for the basic mode of the electromagnetic cavity with a characteristic size of  $W$ . Now, the figure here basically shows the plot of this magnetic resonance wavelength  $\lambda_m$  with respect to the average width  $W$  of the strip of the

## Analytical Model of Magnetic Nanostrips

- Observation:
  - Analytical predictions match the experimental data very well
  - Confirms the validity of the analytical model as a design tool
- Implications:
  - Equations can reliably guide the fabrication of magnetic metamaterials for targeted optical wavelengths
  - Negligible saturation from scaling is observed, enabling structure to produce optical magnetism for even shorter wavelengths

$$\lambda_m \approx 2n_d w \left( 1 + \frac{\lambda_p^2}{4\pi^2 t d} \right) \approx 2n_d w$$

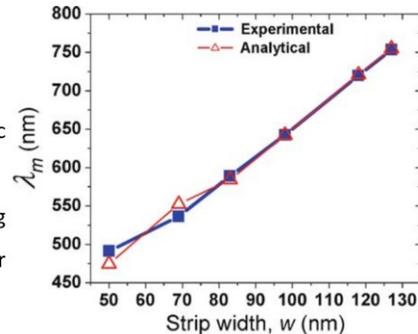


Fig. The dependence of  $\lambda_m$  on the average width  $w$  of the trapezoidal-shaped paired-strip samples.

trapezoidal shaped paired strip samples From both the

## Analytical Model of Magnetic Nanostrips

- Magnetic response strength in paired-strip samples is quantified via effective permeability  $\mu'$  near the magnetic resonance wavelength  $\lambda_m$ .
- Method:
  - Numerical simulations using the homogenization technique
  - Material and geometric parameters ensured good fit between simulations and experimental spectra
- Findings:
  - All samples showed permeability distinct from unity, indicating artificial magnetism
  - Sample F:  $\mu' = -1.6$  at 750 nm (dark-red light)
  - Sample A:  $\mu' = 0.5$  at  $< 500$  nm (blue light)

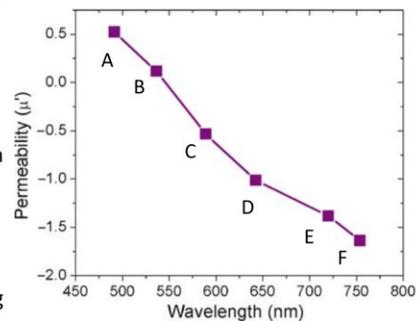


Fig. The minimum values of the retrieved permeability  $\mu'$  at various  $\lambda_m$  for the six samples experimentally studied.

experimental and

## Analytical Model of Magnetic Nanostrips

- Conclusion:
  - The resonance wavelength  $\lambda_m$  is at least  $5 \times$  larger than the strip width  $w$ , confirming their classification as 2D metamaterials at optical frequencies
- Universal structure: Enables generation of optical magnetic responses throughout the entire visible spectrum.
- Design utility:
  - Clear relationship between resonance wavelength and geometric parameters
  - Serves as a general design guide for targeted optical frequencies
- Tunable magnetism:
  - Effective permeability  $\mu'$  can be adjusted by modifying strip coverage
  - Facilitates precise control for different practical applications

analytical approaches.

So, the square ones show the experimental one and the triangle ones show the value from the analytical ones. So, as you can see, the experimental and the analytical calculations are very close when you consider  $W$  effective to be equal to 0.96  $W_b$ . And they are giving you the same trend. So, as you keep reducing the width, your  $\lambda_m$  is basically reducing.

So, more or less, you can play within the entire visible range by changing the width correctly. So, these are the observations. So if you list them you can see that the results obtained from the analytical solutions by using this kind of simple equations matches very closely with those of the experiment ok. So, that basically confirms the validity of this kind of analytical tool for designing. So, what are the implications? The equations can reliably guide the fabrication of magnetic metamaterials for targeted optical wavelengths.

The figure also exhibits negligible saturation due to side scaling, which indicates that such a structure is capable of producing optical magnetism even at shorter wavelengths. So, there is no sign of things getting saturated; that is a good thing. So, with that we understand that the strength of the magnetic response in this kind of paired metallic strips are finally quantified via needs to be quantified via their effective permeability which is  $\mu'$  right near the magnetic resonance wavelength which is  $\lambda_m$ . So, the effective permeability was retrieved using numerical simulations through homogenization technique. For each sample, the material property and the geometrical parameters used in the retrieval process guarantee good agreement between the simulation and the experimental broad band spectrum.

So, here are the findings. So, the minimal values of the permeability for the sixth different samples of the couple strips that we have discussed A to F, A is the thinnest one and F is the widest one ok. So, here you can see the permittivity values for F it is around - 1.6 that is around

dark red light of 750 nanometer wavelength and for the thinnest sample you have it around 0.5  $\lambda$  + 0.5 that is around blue wavelength which is less than 500 nanometer.

So, all samples basically showed permittivity that is very different from unity. And that is telling you about the artificial magnetism, and the two important corner values noted here have already been discussed. So, you can get negative permeability as well and you can get you know permeability very different to one at two different wavelengths just by changing the width of the metallic nanostrips. So, to conclude, you can say that for all the samples, the magnetic resonance wavelength is  $\lambda$  m.

is at least five \* larger than the strip width W. So that basically tells you that the coupled strip samples can be regarded as two-dimensional metamaterials at those wavelength of interest. The experimental and numerical studies of these coupled nanostrips with varying dimensions have offered a universal structure to create an optical magnetic response across the entire visible spectrum. The obtained dependence of the magnetic response and the resonance wavelength on the geometric parameters gives us a general recipe for designing such magnetic metamaterial at any particular optical frequency of interest ok. So, you can make targeted designs, okay. Additionally, it is possible to tune the magnitude of the effective permeability that you saw in the previous slide.

So, you can get  $\mu$  prime based on your requirements just by changing the coverage percentage of the strip. Therefore, the coupled nanostrip structure can serve as a general building block for producing controllable optical magnetism for various practical applications. So with that, we conclude our lecture. So if you have got any queries regarding this lecture, you can drop an email to this particular email address mentioning the course title and the lecture number on the subject line.



*Thank You*

Slides inserted by fallback (review if needed):

