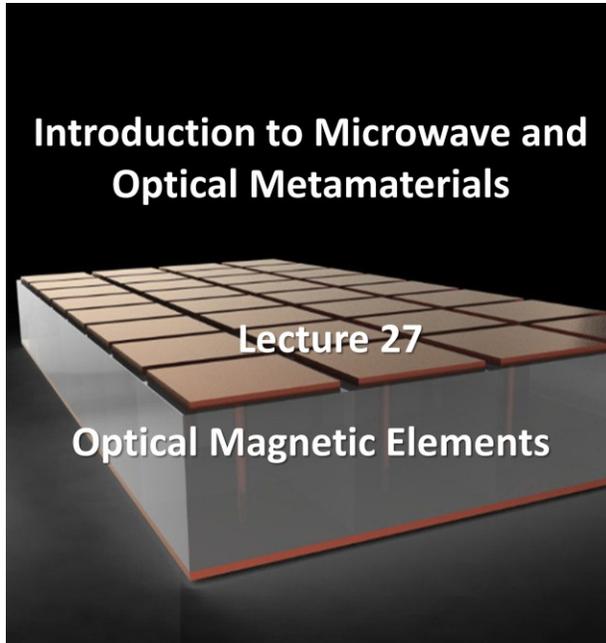


Course Name: Introduction to Microwave and Optical Metamaterials
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Week-6
Lecture-27

Lec 27: Optical Magnetic Elements



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Lecture Outline

- Optical Magnetic Elements
- Pair of Metal Strips as Magnetic Metamaterial



Hello everyone, welcome to lecture 27 of the online course on the interaction of microwave and optical

Optical Magnetic Elements

- Focus: Strategies for extending magnetic metamaterial's operation into the optical frequency range.
- As of early 2009, various structures have been proposed to achieve magnetic responses at higher and higher frequencies.
- Core design principle – unit structure support principal eigenmode with circular current distribution to generate a magnetic moment.
- This magnetic moment causes resonant behavior in the material:
 - Below resonance frequency – magnetic moment parallel with incident magnetic field → effective permeability (μ) > 1
 - Above resonance frequency – magnetic moment is anti-parallel to the incident magnetic field → effective permeability (μ) < 1



Optical Magnetic Elements

- Goal: Achieve magnetic response at higher frequencies without relying on inclined incidence.
- Strategy: Use variations of SRRs—particularly arrays of single SRRs lying in a plane perpendicular to wave propagation.
- In the standard SRR operation, a magnetic field normal to the SRR plane is required to excite the magnetic response.
- In contrast, the single in-plane SRRs can act as magnetic dipoles without any involvement of the incident magnetic field.
- This innovation helps push magnetic resonance into the optical regime.

Optical Magnetic Elements

- The different orientations of SRRs with respect to the external field are illustrated in the figure.
- The standard application of SRRs with an H field component penetrating the SRR plane is shown in Fig. a.
- Major limitation: Fabrication difficulties arise when trying to construct these structures using micro or nano-fabrication techniques, due to alignment and scale constraints.

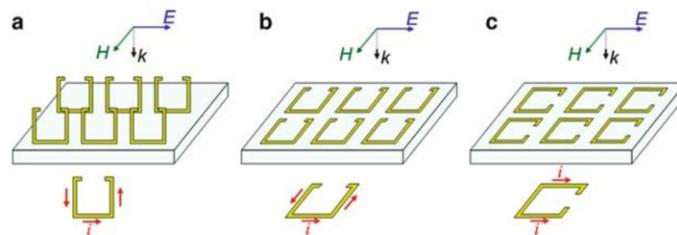


Fig. Different orientations of single SRR arrays.

Optical Magnetic Elements

- Figures b and c show SRR arrays lying on a substrate, which is compatible with standard lithography and deposition techniques.
- In both configurations, the applied magnetic field is parallel to the SRR plane and cannot induce magnetic dipoles.
- However in Fig. b, if the electric field aligns with the gap-bearing side – asymmetric currents form in the SRR arms, creating a magnetic dipole.
- In Fig. c, with the electric field along the SRR arms, identical currents flow, preventing the formation of a loop current and hence no magnetic dipole is generated.

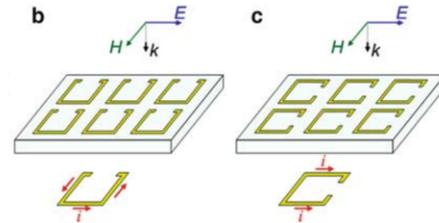


Fig. Different orientations of single SRR arrays.

metamaterials. Today's lecture will be on optical and magnetic elements. Here is the lecture outline, we will discuss about optical magnetic elements and we will also see in details a pair of metal strips that can work as magnetic metamaterial. So, in this lecture, we will discuss different routes for pushing the operational frequency of magnetic metamaterials into the optical regime. So, the basic principle behind these designs is that the unit structures can support a particular eigenmode with a circular kind of distribution. That gives rise to a magnetic moment, okay.

So, in early 2000 various structures have been basically proposed to achieve magnetic response at higher and higher frequencies because that is where the challenge lies right. So, such a magnetic moment that can come from a circular kind of distribution can introduce resonant behavior for the structure. So, we will see that the magnetic moment is parallel to the incident magnetic field and this gives rise to permeability greater than 1 for the frequencies below the resonance frequency. On the other hand, you will see that above the resonance frequency, the magnetic moment is basically anti-parallel to the incident magnetic field.

That means it is in the opposite direction, and that produces an effective permeability of less than 1. So, in order to obtain a metamagnetic response at higher frequencies, that means a metamaterial response at higher frequency for the magnetic permeability. Without playing the trick of inclined incidence, okay, which we have seen earlier for the terahertz metamaterial, different variations of the splitting resonators can be used and that is what people have seen, right. So, one of the most important designs for achieving magnetic resonance toward optical regime is basically based on arrays of single SRRs which are lying in a plane perpendicular to the wave propagation okay. So, in the standard SRR operation a magnetic field normal to the SRR plane will be required to excite the magnetic response and in contrast The single in-plane SRR can also act as magnetic dipoles without any involvement of the incident magnetic field.

So, this one is basically coming from the electric field. So, we will show you the details of these

two things together in the next few slides. Now, this particular innovation has basically helped push magnetic resonance into the optical regime. So, this particular figure illustrates the different orientation of single SRR arrays which I was talking about with respect to the external fields which are also shown in each of these figures. So, the first figure, Figure A, basically shows standard SRR operation, where you will see the magnetic dipole can be excited.

by the external magnetic field itself because the field is in this direction, and these SRRs are basically normal to this field. Now the major limitation in this kind of a design is that there are fabrication difficulties because you have to you know this kind of rings are basically perpendicular to this plane. So, when you try to construct these structures using micro-nano fabrication. There are challenges coming from alignment and scale constraints. So, this vector clearly tells you how the field is interacting with the structure.

You have the magnetic field in this direction, you have the electric field in this direction, and the field is falling normally on this particular substrate. Now, there are also two other configurations possible, which I will discuss briefly. So, here you can see in figures B and C that these are also SRR arrays. Now, these are not you know sticking upwards from the substrate rather they are basically lying on the substrate and that is compatible with the standard lithography and deposition techniques. So, what you will see here in this particular configuration is that you have the electric field in this direction and the magnetic field in this direction, right? So, figure B is particularly interesting because here what you will see that the electric field is basically parallel to the gap bearing arm of the SRR right.

So, that will basically give you a asymmetric current distribution or asymmetric current mode in the two arms of the rings and because of that a magnetic dipole can be obtained okay. Now, in both of these cases, the magnetic field is parallel to the SRR. So, it is not inducing any magnetic dipole moment. So, who is inducing the magnetic dipole in case B, which is the electric field? Because this electric field which is aligned to the gap bearing side induces asymmetric current in the you know splitting resonator arm okay and that is giving you the magnetic dipole. Now, if you see here in figure B, the electric field is basically polarized along the two arms.

So, in that case, symmetrical or identical currents are basically excited in the two arms of the splitting resonator. So, in that case, no loop current will flow, and you cannot generate a magnetic dipole. Okay. So, this is the structure that will not give you any magnetic moment at all. So, this is something interesting to understand: in the first case, the magnetic field was exciting the magnetic dipole.

In this particular case the electric field is exciting the magnetic dipole, but in this case the electric field is not doing the excitement of the magnetic dipole right. So, this will not show any kind of magnetic moment. Now, let us go into details of this optical magnetic elements and let us see how we can understand the

Optical Magnetic Elements

- Planar single SRRs can be analyzed using an equivalent LC circuit model.
- SRR as shown in figure can be viewed as an LC oscillator.
- The ring acts as an inductor, and the gap serves as the capacitor.
- Two ways to excite resonance in this LC oscillator:
 - Magnetic field vector penetrates the ring (inductor) → Fig. a
 - Electric field vector aligns with the gap (capacitor plates) → Fig. b
- In Fig c, neither the inductor nor the capacitor aligns with the external field, so no resonance occurs.

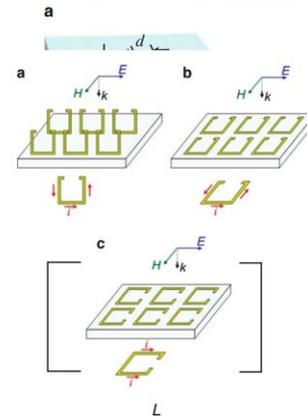


Fig. (a) A single-SRR as a magnetic element and (b) its equivalent LC circuit.

resonance of this kind of structures using equivalent LC. Circuit model that will allow us to correlate the resonance frequency with the physical parameters of the structures, okay. So, this is the case of a single SRR splitting resonator as a magnetic element.

So, besides the current symmetry considerations, the underlying physics in this planar SRR can also be interpreted using this kind of equivalent circuit model. And the discussion closely follows the work on metamagnetics at 100 terahertz, right? So, as discussed earlier, a split ring resonator can be represented as an LC oscillator. So, you will see that the ring here basically acts as the inductor, L. And the gap gives you the correct capacitance. So, for such an oscillator, there are basically two means of exciting the resonance.

The first one is this one which you have already seen where the magnetic field vector must penetrate the inductor okay that is a coil and that will give you the magnetic moment okay and in the second case the electric field vector should align with the gap So, that is the you can say that the electric field vector must be aligned normal to the capacitor plate that is you know the surface of the cut and that will also give you the magnetic moment. Now, the third case obviously is not doing any good. Okay. Because in this particular case neither inductor nor capacitor aligns with the external fields and that is why you know you do not see any kind of resonance from this kind of structure right. So, what is important to remember here is that these two will give you some resonance.

This is a direct excitation from the magnetic field; this is an excitation of the magnetic dipole from electric, but this one is not giving you any resonance behavior. So, now let us look into the structure where people have fabricated this and they have shown the magnetic resonance with this case B that is electric field excitation. So, obviously, the electric field has to be excited along the gap like this. So, this is the solid line that shows you this polarization.

Okay. And here, because of this, they were able to excite the magnetic moment of the magnetic dipole at the mid-infrared wavelength of 3 microns. So, this is the result of an experiment where the split-train resonators typically have dimensions of 320 nanometers. Okay. So, the figure clearly shows that you have the red one is the transmission, the blue one shows the reflectance spectrum of this kind of an array of single split trend resonator. And these are the two polarizations you have considered.

So, one is this parallel polarization; the other one is this orthogonal one. So let us study this. Here you can see clearly that you have this magnetic resonance, but as soon as you change the polarization to 90 by 90 degree, are basically now along this dotted direction which is also shown here. And here you can clearly see that the resonance the magnetic resonance disappears completely and that is in very good agreement with what we have just discussed now analytically. Now, these are in mid infrared wavelength, so much longer wavelength, so you want to you know shift it towards visible range, so what you can do by further reducing the size of the SRRs, magnetic resonances based on this principle have been achieved from far infrared To the long-wavelength end of the visible spectrum.

So, you are actually getting closer to optical frequencies. Now, it is important to note here that this kind of electrically coupled magnetic resonance is basically an indirect one and it is inevitably weaker compared to the magnetic resonance that is excited directly by the magnetic fields. So, the retrieved effective parameters show that you have got very minimal value of effective permeability around this 3 micrometer range and the value is typically around 0.8 which is close to that of the non-magnetic medium.

Right. So, this is a major reason why this metamagnetics in planar single assurers cannot be used in many interesting applications something like artificial magnetism or negative index materials or electromagnetic cloaking because the permeability that you are getting is very very low. Another serious drawback of this kind of planar assurers is the background of the geometrical scaling. And the subsequent saturation of the resonance frequency. So, you cannot keep scaling it down and move the resonance frequency to the optical regime or even higher frequencies; that does not work. So, this saturation basically effect fundamentally this saturation effect basically fundamentally prevents the SRRs for from providing magnetic response at the true optical frequencies which is basically the visible range.

Now, the scaling background of this kind of single SRR is described mainly by linking to the kinetic energy and the self inductance of electrons which basically come from the resonance behavior of the noble metal that you are going to use in the optical frequency regime right. So, this findings are basically supported by equivalent circuit analysis and saturation effect comes out to be an intrinsic property of an SRR as in resonator and it is basically independent of how split this splitting resonators are basically getting excited right. So, the analysis will apply to both the planar reserrers that are electrically coupled magnetic response as well as for the you know splitting resonators which were sticking out where you are actually using the magnetic field to directly excite the magnetic resonances, right. So, the saturation effect is basically an intrinsic property, and it is completely independent of the kind of excitation you are using.

Now let us look into this resonator in terms of its physical properties in more detail. So as we consider this single splitting resonator, which basically works as an LC resonator. And you can see that the magnetic resonance basically occurs at the eigenfrequency $\omega_m = 1/\sqrt{LC}$. So, to the first order approximation, you can obtain the equivalent lumped elements of an LC circuit where you can consider inductance to be equal to $\mu_0 L^2/T$, L is basically this length, T is the thickness. Okay, and the capacitance C is basically coming from $\epsilon_0 W/T$; W is the width, T is the thickness, and T is the gap between the or the split, okay.

So, what do you see here is that all these physical parameters are giving you equivalent inductance and capacitance, and that determines the magnetic resonance frequency of your splitting resonator. Now, here we'll do one thing. We'll use A to denote the unit cell size of the single SRR. And this A will also serve as a scaling factor, right? Because all the geometrical parameters, such as length, gap, thickness, and width, will also vary in proportion to the unit cell size. So, if you consider this as your unit cell, everything will scale down with your unit cell size A .

So, you can simply write that L and C both will scale with A . And with that, you can find an important relation that the resonance frequency will basically scale inversely with the SRR size. So, you can write $\omega_m = 1/\sqrt{L^2/T \cdot \epsilon_0 W/T}$ square root D by WL square it will be proportional to $1/E$. So, more you scale you can shift your frequency towards Now, this is a very simple expression and it allows you the basic scalability, it tells you about the basic scalability of this kind of SRRs across various frequency regime and you just need to remember that the resonance frequency is inversely proportional to the size of the unit cell of the SRR, right. Now, this simple but crude reasoning, however, is based on the assumption that perfect metal with infinite carrier density is being used, okay.

So, in this case, the current excited by the external field is basically carried by electrons with zero electron velocity. But if you see in real metals, they will have finite electron density and hence a finite plasma frequency. Therefore, there must also be a finite electron velocity that is proportional to the current I in the loop. Hence, you also have to think of an additional kinetic inductance, which is L_{kin} . That will account for the total energy of the moving electrons, right? So, derivations will show that you know additional inductance L_{kin} is also inversely proportional to the scaling factor K .

So, as a result the magnetic resonance frequency ω_m will now take this particular form that you need to write it as $1/\sqrt{L + L_{kin}} \cdot C$. So, what happens you know you will get L and L_{kin} you have the inverse proportionality with A , so with that you know and all these things you can get into this particular factor which will give you $1/\sqrt{A^2 + \text{constant}}$. So, this constant is basically coming from the product of C and L_{kin} , which is the origin of the scaling saturation in the splitter resonators. Now, this will show that you know the maximum achievable resonance will be near $2\pi \cdot 373$ terahertz, which is typically around 800 nanometers in wavelength. That is where you can go maximum with this kind of single SRR approach, and that limits the SRRs at visible optical frequencies, right? Because the optical

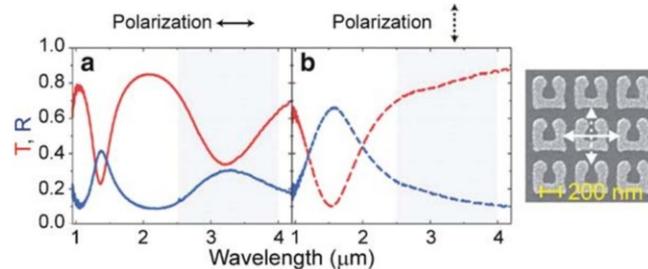
frequency is below 800 nanometers, typically between 400 and 800 nanometers, this is where this kind of design cannot take you.

So, an intrinsic limit to this scaling of SRF size for obtaining the magnetic resonance in optical range has actually pushed the researchers to break the barrier and look for alternative designs of magnetic meta atoms. So, the objective here is to find a structure that can fulfill the following requirements. First, it should be compatible with the existing nanofabrication techniques. Secondly, the magnetic resonance if it is possible get it excited by the external magnetic field directly, because that will give you much stronger magnetic response ok. And you need to ensure negligible saturation effects at high frequency, so the scaling is possible, right? So, an alternative structure people have thought of to the typical double splitting resonators is to like fabricate a staple like gold structure, separated from a continuous gold film as you can see in the figure.

So, here the structure basically consists of an array of gold staples that are separated from a continuous gold film by a zinc sulfide spacing layer. So, this kind of staple will be interacting directly with the incident magnetic field and can give you a stronger magnetic response. So, here is an array of nanostaples with mid-infrared magnetic response, and this is the length scale that shows you the

Optical Magnetic Elements

- Magnetic resonance with electric field excitation has been achieved in the mid infrared wavelength of $3 \mu\text{m}$.
- Experimental results (Figure) show this effect using single SRRs with $\sim 320 \text{ nm}$ dimensions.
- Rotating the E-field polarization by 90° eliminates the magnetic resonance, validating the excitation mechanism.
- Smaller SRRs have enabled magnetic responses across a broad spectrum (far-infrared to visible wavelengths).

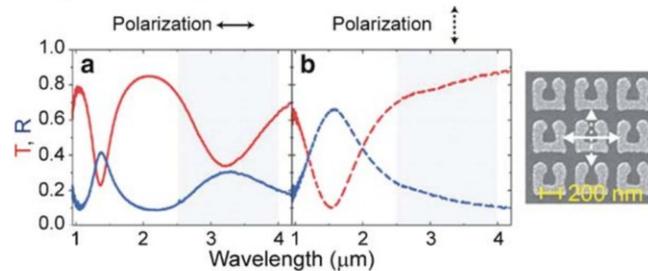


dimension of the nanostaples. Right. So, this design basically maintains magnetic activity without suffering the drawbacks that you have seen in the scaled-down SRRs, okay.

So, from an equivalent circuit point of view the upper loop of the staple ok this part ok basically works as an inductance while the staple footing okay will serve as the capacitors okay and the each staple can be viewed as a pair of staples facing each other due to the uniform gold film is basically acting as an imaging mirror right. Now, the experimental demonstration basically used an array periodicity of 600 nanometer and a Lorentz resonance in effective

Optical Magnetic Elements

- Electrically coupled magnetic resonance is indirect and weaker than direct magnetic excitation.
- The effective permeability minimum near the 3 μm resonance is around 0.8, close to that of a non-magnetic medium.
- This weak magnetic response limits the use of planar single-SRRs in key applications like negative-index materials and electromagnetic cloaking.



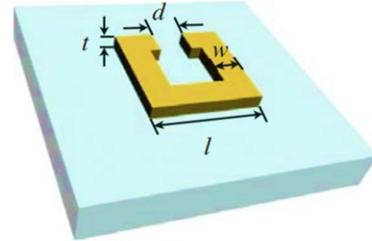
permeability was observed where a minimum value of - 0.5 was recorded at 65 terahertz. Now, what you can see that the magnetic activity in this kind of nanostable structure is much stronger than that of the planar splitting

Optical Magnetic Elements

- Planar SRRs suffer from resonance frequency saturation, limiting their function at visible (true optical) frequencies.
- Scaling breakdown is linked to the kinetic energy and self-inductance of electrons which results from the plasmonic behavior of noble metals in the optical regime.
- These findings are supported by the equivalent circuit analysis.
- The saturation effect is an intrinsic property of an SRR as a resonator, and is independent of how the SRR is excited.
- So, the analysis applies to both the planar SRRs with an electrically coupled magnetic response as well as the standard SRRs whose response is driven by the external magnetic field directly.

Optical Magnetic Elements

- The single SRR acts as an LC resonator with a magnetic resonance at $\omega_m = 1/\sqrt{LC}$
- Equivalent inductance and capacitance:
 - $L = \mu_0 l^2 / t$
 - $C = \epsilon_0 w t / d$
- All geometrical parameters (length ' l ', gap ' d ', thickness ' t ', width ' w ') vary in proportion to unit cell size ' a '.



- Therefore, resonance frequency scales inversely with SRR size:

$$\omega_m = c_0 \sqrt{d/wl^2} \propto 1/a$$

- This relationship reflects the basic scalability of SRRs across different frequency regimes.

resonators that we discussed in the previous section ok. Because the staples are basically standing up, splitting resonators that could directly couple to the external magnetic field, okay.

So, obviously, the standing-up geometry will facilitate stronger interaction with the magnetic component of light. In the previous case, it was the electric field who was giving you that you know magnetic moment, here you are directly getting it from the magnetic component of the light. So, simulations have also shown that it is possible to extend negative permeability to higher

Optical Magnetic Elements

- The initial scaling analysis assumes a perfect metal with infinite carrier density and zero electron velocity.
- Real metals have finite electron density, leading to finite electron velocity proportional to the current ' I ' in the loop.
- Hence, there is additional kinetic inductance L_{kin} that accounts for the total kinetic energy of the moving electrons.
- L_{kin} is inversely proportional to the SRR's scaling factor ' a '.
- The total resonance frequency becomes $\omega_m = 1/\sqrt{(L + L_{kin})C} = 1/\sqrt{a^2 + const}$
- This leads to a maximum achievable resonance near $2\pi \times 373$ THz (~ 800 nm wavelength), limiting SRRs at visible optical frequencies.

Optical Magnetic Elements

- The scaling limitations of SRRs in the optical range led to the search for alternative magnetic meta-atom designs.
- Key requirements for the design:
 - Compatibility with nanofabrication methods
 - Direct magnetic resonance excitation by an external magnetic field
 - Minimal saturation effects at high frequencies
- Alternate solution: a staple-like gold structure separated from a continuous gold film by a ZnS spacing layer.
- This design maintains magnetic activity without the drawbacks seen in scaled-down SRRs.

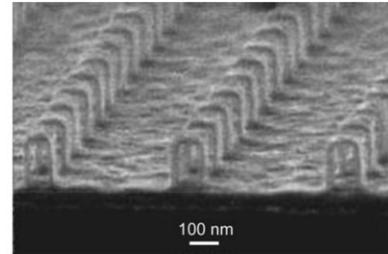
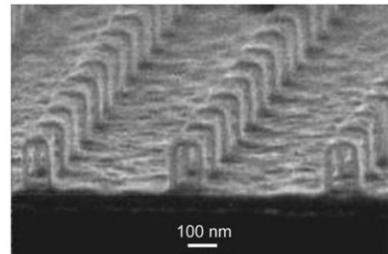


Fig. Array of nano-staples with a mid-infrared magnetic resonance.

frequencies of near infrared range say up to 1.3 micrometer by reducing the pitch size that is basically the array constant or the lattice constant and the dimensions of the arrays okay. More advanced artificial elements for magnetic

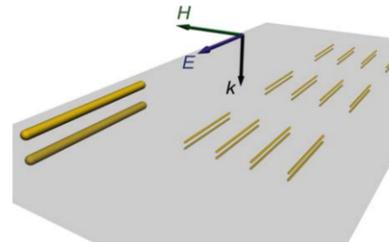
Optical Magnetic Elements

- In equivalent circuit terms:
 - The upper loop of the staple acts as inductance
 - The footings serve as capacitive elements
 - Each staple can be viewed as a pair of staples facing each other due to the uniform gold film acting as an imaging mirror
- Experimental setup:
 - Array periodicity: 600 nm
 - Observed Lorentz resonance in effective permeability with a minimum value -0.5 at ~ 65 THz
- Advantages over planar SRRs:
 - Stronger magnetic activity due to direct coupling to the external magnetic field
 - Standing-up geometry facilitates better interaction with the magnetic component of light



Optical Magnetic Elements

- Simulation insights:
 - Negative permeability can be pushed into near-IR range ($\sim 1.3 \mu\text{m}$) by reducing array pitch and feature dimensions
- Advanced magnetic metamaterial designs include:
 - Pairs of metallic rods, plates, or strips
 - These support principal eigenmode with an anti-symmetric current distribution in the coupled system
- Optical diamagnetism in nanorods was first predicted in 2002 – consists of pairs of parallel metallic nanorods.
- An oscillating magnetic field passes through the gap between rods, exciting current loops.



Pair of Metal Strips as Magnetic Metamaterial

- Nanorod specifics:
 - Typically fabricated with electron-beam lithography and direct deposition
 - Cross-sections are often thin rectangles or trapezoids
 - Often referred to as cut-wire pairs or plate pairs in literature
- Square plate pairs:
 - Help eliminate polarization anisotropy
 - Negative effective permeabilities have been demonstrated in the near-IR range ($1.0 - 1.5 \mu\text{m}$)
- One of the most successful magnetic metamaterials proposed thus far is the pair of metal strips shown schematically in the figure.

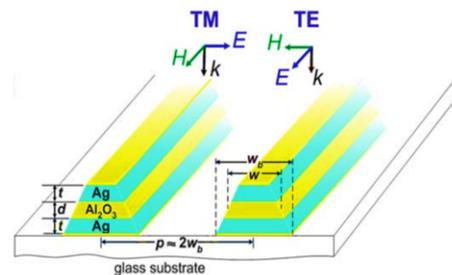


Fig. Schematic of the structure consisting of coupled nanostrips.

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.

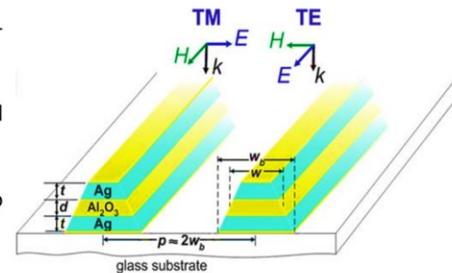


Fig. Schematic of the structure consisting of coupled nanostrips.

metamaterials could include, you know, arrays of pairs of metallic rods, plates, and strips, okay.

So, each of these structures is basically capable of supporting a principal eigenmode with an antisymmetric current distribution in the coupled system. So, here is an example of how it looks, okay. So, this kind of optical diamagnetic response was first predicted in pairs of metallic rods okay and that in 2002. So, a composite comprising pairs of parallel nanorods as you can see here So, in this case this is the direction of the electric field, this is the direction of the magnetic field that is basically normal to this pair and this is where the field is incidenting k vector. So, what is important is that this kind of orientation is required.

So, the magnetic field basically oscillates through the gap between the rods, and it can excite a loop current. Okay, in each pair of the rod like this, okay. So, such a nanorod system may also exhibit a negative index of refraction. So, this is a structure or a composite. So, you can see this is a nanorod array that is in a dielectric medium, and this composite can give you optical diamagnetism, right? Now, in the actual fabrication of paired nanorod arrays using electron beam lithography and direct deposition, you will see that the cross section of each rod would become a thin rectangle or trapezoid kind of thing.

That means you know and you have to make sure that the thickness is kind of much smaller than its length and width. So, they are basically you know this nanorod pairs are becoming like cut wire pairs or plate pairs and this is how they are also referred to in the literature ok. So, sometimes square-shaped plate pairs are also favored because this particular geometry eliminates undesirable polarization and isotropy in the metamaterial, right? And negative effective permeabilities from this kind of square nanoplate arrays have been observed at this near infrared range which is from 1 to 1.5 micron okay and they have given negative effective permeabilities okay. So, one of the most successful magnetic metamaterials that have been proposed thus far.

is a pair of metallic strips which are shown here you can see this is a gold strip, then you have a alumina spacer that is separating this bottom and the top strip ok. So, this is typically a trapezoidal cross section, and these are the two possible polarizations: here, the magnetic field is along the length. So, it is fine; we can see that in the next one also. So, here you have the magnetic field along the length, and here you have the magnetic field across this length, okay. So, what you can see here that the nanostrip these are called the nanostrip magnetic metamaterial okay which is made of this kind of a pair of metallic nanostrips which are separated by the dielectric spacer.

So, notice that the upper and lower strips are not identical. So, the overall cross section of the strip pair is basically trapezoidal in shape, this is basically due to the fabrication process. And under TM illumination, you will see that the nanostrips show both magnetic and electric resonance, and the magnetic field is basically along the strip. Okay. But under TE polarization, you will see that only the electric field is along the strip and no resonance basically occurs in this particular case.

Now, the fabrication of such nanostrips is typically achieved using electron beam lithography and vacuum deposition. So, we will stop here in this lecture and we will continue discussing the analytical models and other details of these magnetic nanostrips in the next lecture. So, if you have any queries regarding this, drop an email to this email address mentioning the course number and lecture number in the subject line. Thank you.





Thank You