Course Name- Nanophotonics, Plasmonics and Metamaterials

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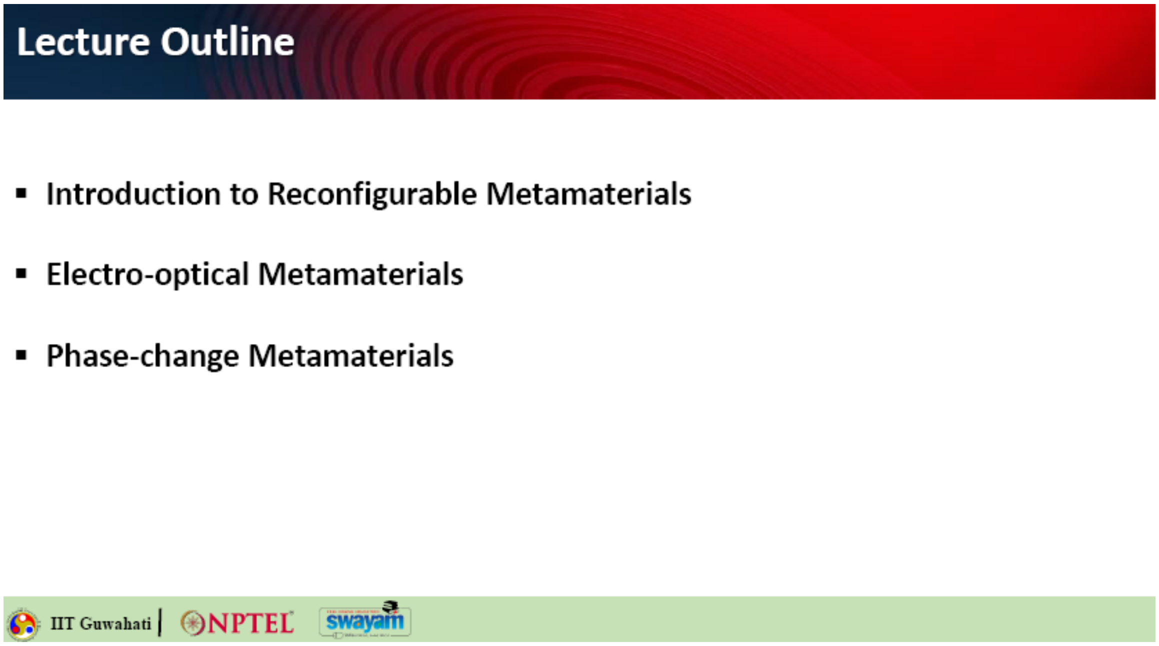
Week-09

Lecture -27

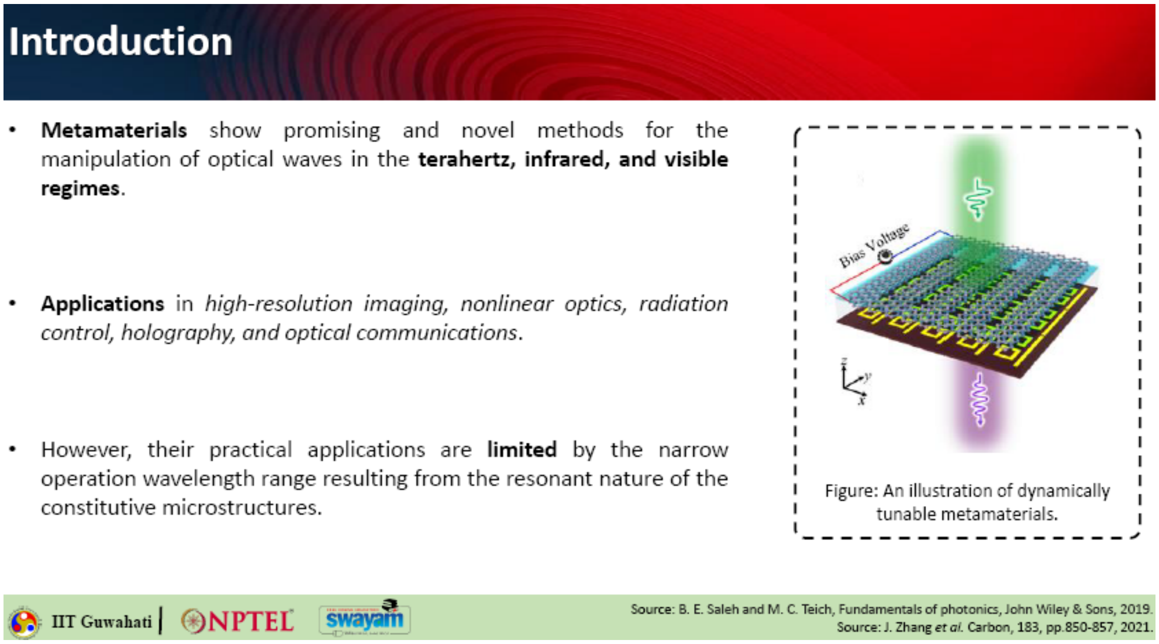
Hello students, welcome to lecture 27 of the online course on Nanophotronics, Plasmonics and Metamaterials. Today's lecture will be on tunable photonic metamaterial based devices. So this is the lecture outline. We'll first talk about introduction to reconfigurable metamaterials. Then we'll take some examples of electro-optical metamaterials and phase change metamaterials. So first of all, we have seen metamaterials in our previous lectures and we have seen that metamaterials show promising and novel methods for manipulating optical waves in terahertz, visible and infrared spectrum.



Lecture Outline

- Introduction to Reconfigurable Metamaterials
- Electro-optical Metamaterials
- Phase-change Metamaterials

Now these metamaterials can be of different types that we have seen previously, double positive, single negative and also they can give negative refractive index, negative epsilon and near zero, different effects can be obtained from metamaterials. Now what are the applications? The applications are typically in the areas of high resolution imaging, non-linear optics, radiation control, holography, optical communication and so on. Now if you think of the design of the metamaterials, it is basically based on the design of the unit cell that is meta-atom. Now in most of the cases, the practical applications become limited because once you fabricate this metamaterial, you cannot change it.



Introduction

- **Metamaterials** show promising and novel methods for the manipulation of optical waves in the **terahertz, infrared, and visible regimes**.
- **Applications** in *high-resolution imaging, nonlinear optics, radiation control, holography, and optical communications*.
- However, their practical applications are **limited** by the narrow operation wavelength range resulting from the resonant nature of the constitutive microstructures.

Figure: An illustration of dynamically tunable metamaterials.

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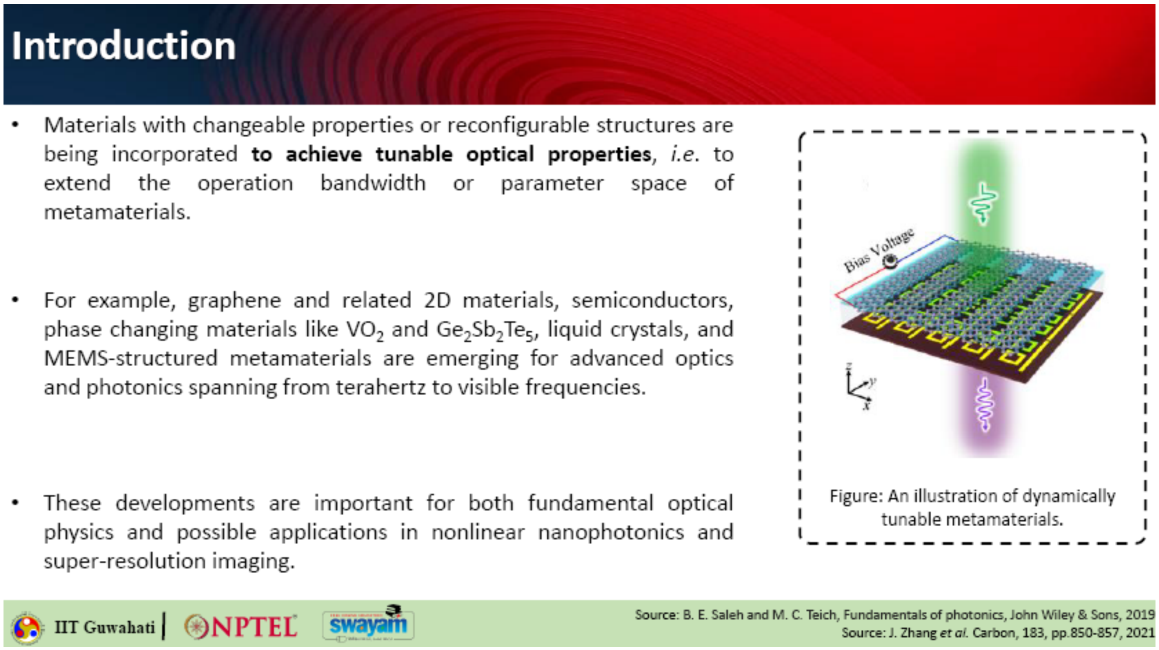
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: J. Zhang *et al.* Carbon, 183, pp.850-857, 2021.

So in that case, the resonance typically that you obtain from a metamaterial is a narrow band resonance and that comes from the resonating nature of the constituent microstructures or nanostructures whatever depending on the frequency range you are talking about. Now what is important is to have a reconfigurable metamaterial. By reconfigurable it means that you can put some external stimuli and you should be in a position to change the resonance wavelength without going through the fabrication of the device again. So that brings us to an interesting topic of reconfigurable metamaterials. So here is a schematic as you can show.



Introduction

- Materials with changeable properties or reconfigurable structures are being incorporated **to achieve tunable optical properties**, *i.e.* to extend the operation bandwidth or parameter space of metamaterials.
- For example, graphene and related 2D materials, semiconductors, phase changing materials like VO_2 and $Ge_2Sb_2Te_5$, liquid crystals, and MEMS-structured metamaterials are emerging for advanced optics and photonics spanning from terahertz to visible frequencies.
- These developments are important for both fundamental optical physics and possible applications in nonlinear nanophotonics and super-resolution imaging.

Figure: An illustration of dynamically tunable metamaterials.

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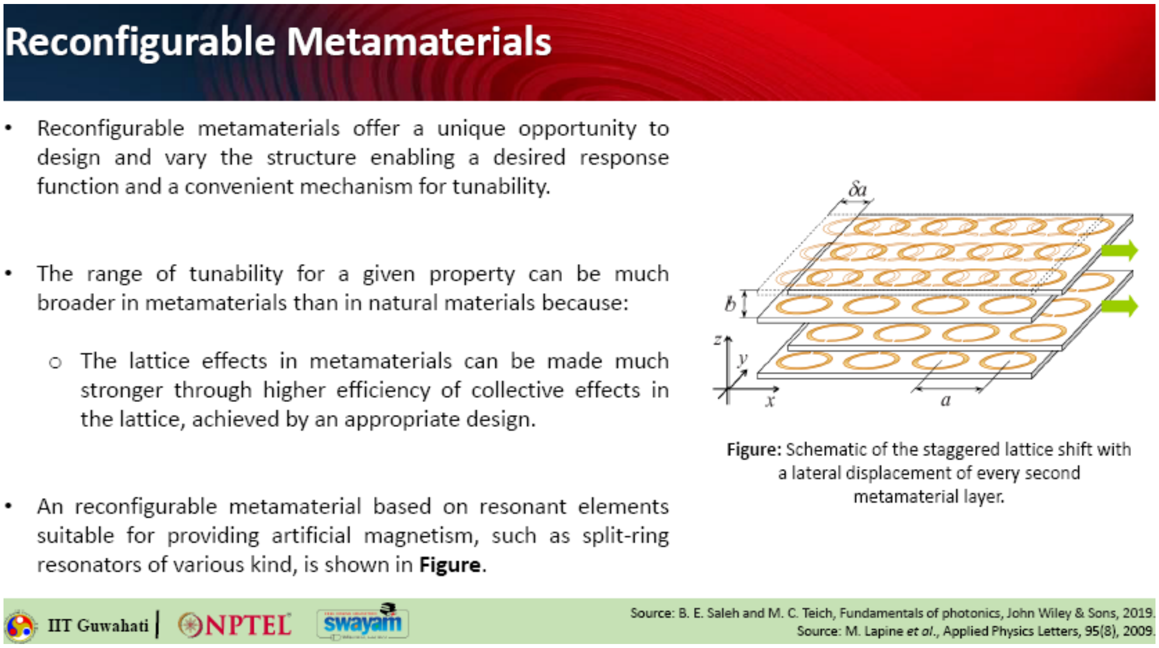
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019
Source: J. Zhang *et al.* Carbon, 183, pp.850-857, 2021

So at the bottom there is a metamaterial and then there is a kind of 2D material, it may be graphene or any other material, which is close to this particular metamaterial that you have fabricated. And there can be a voltage biasing on this 2D material and that will change the surrounding medium permittivity of these meta-atoms. And that can give rise to some kind of dynamic effect which will change the response of this particular metamaterial at a given voltage. So if you change the voltage the response will also change and that is how the same metamaterial will be able to provide you different different responses depending on the tuning of the bias voltage that you are applying. So this is the main concept of reconfigurable metamaterial.

It means the same metamaterial can be used for different applications. You do not need to undergo the fabrication process again. You can reuse the same metamaterial by reconfiguring it by setting up a specific bias voltage depending on your requirement. So we are looking for some materials which have got some changeable properties or some reconfigurable structures where mechanically you can change some structure and then when I say mechanically these are basically MEMS kind of arrangement, micro-electromechanical systems or NEMS kind of arrangement. So, there you can achieve some kind of tuning of the optical properties of these metamaterials.



Reconfigurable Metamaterials

- Reconfigurable metamaterials offer a unique opportunity to design and vary the structure enabling a desired response function and a convenient mechanism for tunability.
- The range of tunability for a given property can be much broader in metamaterials than in natural materials because:
    - The lattice effects in metamaterials can be made much stronger through higher efficiency of collective effects in the lattice, achieved by an appropriate design.
- An reconfigurable metamaterial based on resonant elements suitable for providing artificial magnetism, such as split-ring resonators of various kind, is shown in **Figure**.

Figure: Schematic of the staggered lattice shift with a lateral displacement of every second metamaterial layer.

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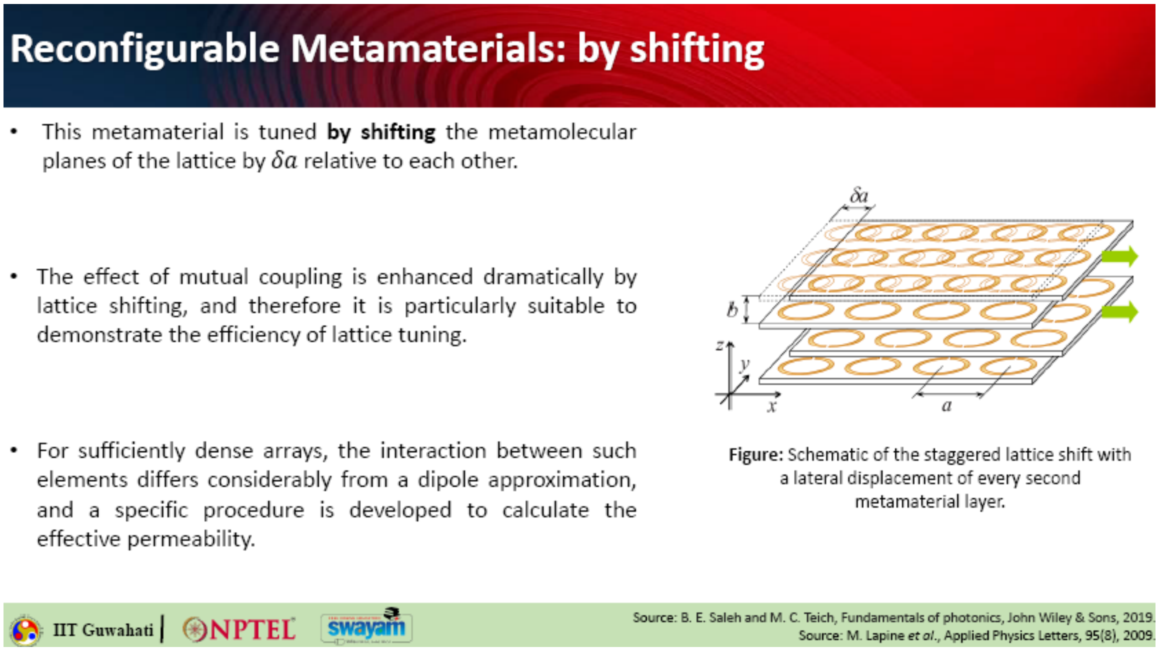
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: M. Lapine *et al.*, Applied Physics Letters, 95(8), 2009.

Now here as I mentioned that one way is to use graphene or other 2D materials. Then you can use semiconductors, you can use phase changing materials like vanadium dioxide or GST, gallium, tin, tellurium. You can use liquid crystals, you can use different kind of MEMS structured metamaterials. So these are all used for emerging applications in advanced optics and photonics and the operating range of frequencies can be tuned between terahertz to visible. And these developments are important both for fundamental optical physics and their applications in nonlinear nanophotonics and say super-resolution imaging and so on.

So we will take an example of reconfigurable metamaterial and discuss it in more details. So here we understood that reconfigurable metamaterials they offer a unique opportunity to design and vary the structure enabling a desired response function and a convenient mechanism for tunability. Now that is something very important that convenient mechanism for tunability. If there is a voltage requirement which comes down to kilovolt or several hundreds or thousands of volts then it is an impractical design. You will not be using a metamaterial along with such high voltage source.

So you have to think of some mechanism where sub-5 volt or say few tens of volts that is also a bit high but still manageable. So that kind of external stimulus should be able to bring the tunability. The other kind of tunability can be from the case where you have a metamaterial lattice and you are able to dislocate the lattice by some means. So the range of tunability for a given property can be much broader in metamaterials than in natural materials. So that is what we understood because here you have the control over the meta-atom design and its periodicity or the lattice kind of arrangement.



Reconfigurable Metamaterials: by shifting

- This metamaterial is tuned **by shifting** the metamolecular planes of the lattice by δa relative to each other.
- The effect of mutual coupling is enhanced dramatically by lattice shifting, and therefore it is particularly suitable to demonstrate the efficiency of lattice tuning.
- For sufficiently dense arrays, the interaction between such elements differs considerably from a dipole approximation, and a specific procedure is developed to calculate the effective permeability.

Figure: Schematic of the staggered lattice shift with a lateral displacement of every second metamaterial layer.

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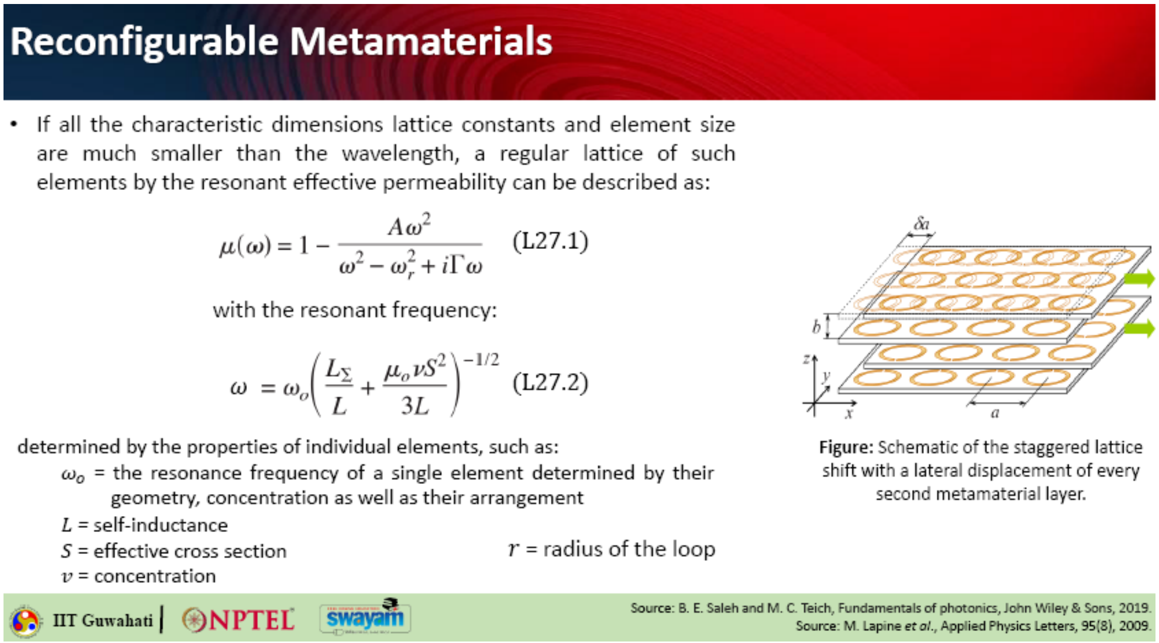
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: M. Lapine *et al.*, Applied Physics Letters, 95(8), 2009.

So when you see the lattice effects in metamaterial they can be actually made much stronger through higher efficiency of collective effects in the lattice and that can be achieved by doing appropriate design. So reconfigurable metamaterial based on resonant elements can be suitable for providing artificial magnetism such as split-trim resonator array that you have already seen. So we can actually start with this kind of a simple metamaterial design and we can see here that alternative layers can be staggered and the lattice can be slightly shifted. So here you can see the structure carefully that the lattice period is basically a and the gap between the two planes or the two layer is b and the amount of shift is given as delta a and these are the coordinate system that has been marked. So what you see here this is basically a reconfigurable metamaterial by shifting the lattice.

So in this case you are basically shifting the metamolecular plane so you can call this one plane as a metamolecular plane or simply you can call meta-atom plane. They do not make much difference how do you call them but what is main important thing here is that you are basically changing the lattice orientation and this is where metamaterial field becomes so cool because in natural materials the lattice positions are fixed you will not be able to alter them. But here you can actually design the meta-atom on like depending on your need and then you are also able to move their lattice positions to fine tune their optical response. Now what happens when you do this when the lattice positions are shifted the effect of mutual coupling is basically enhanced and that enhances dramatically when you do the shift and bring them closer to each other in one way or the other and it can show you a very high efficiency lattice tuning. So, for sufficiently dense arrays the interaction between such elements differs considerably from a dipole approximation.



Reconfigurable Metamaterials

- If all the characteristic dimensions lattice constants and element size are much smaller than the wavelength, a regular lattice of such elements by the resonant effective permeability can be described as:

$$\mu(\omega) = 1 - \frac{A\omega^2}{\omega^2 - \omega_r^2 + i\Gamma\omega} \quad \text{(L27.1)}$$

with the resonant frequency:

$$\omega = \omega_o \left(\frac{L_\Sigma}{L} + \frac{\mu_o \nu S^2}{3L} \right)^{-1/2} \quad \text{(L27.2)}$$

determined by the properties of individual elements, such as:

ω_o = the resonance frequency of a single element determined by their geometry, concentration as well as their arrangement

L = self-inductance

S = effective cross section

ν = concentration

r = radius of the loop

Figure: Schematic of the staggered lattice shift with a lateral displacement of every second metamaterial layer.

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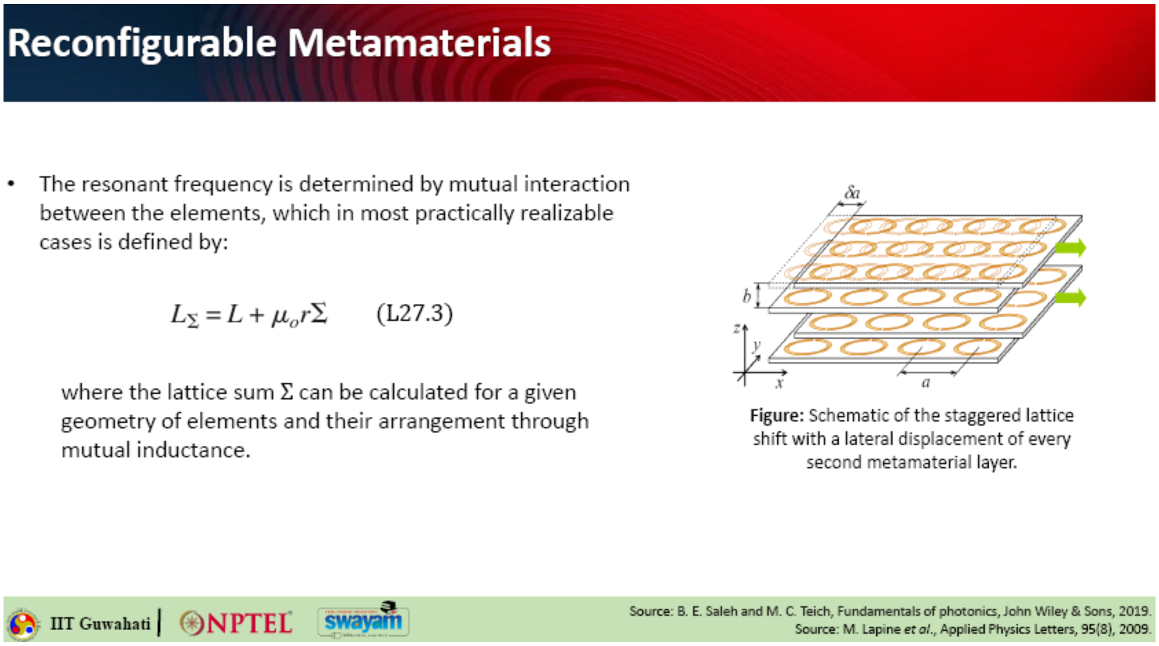
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: M. Lapine *et al.*, Applied Physics Letters, 95(8), 2009.

So here you can always think of multiples which are interacting because the interaction becomes very strong and only dipole approximation will not be able to consider all the effects so there are multipolar, multipole means quadrupole octopole and so on they are also interacting with each other. So that actually gives you the coupling and then there is a specific process that can be developed to calculate what is the effective permittivity of this material. When you finally want to know the optical response you need to find out what is the effective permittivity of a particular material. Now if all the characteristic dimensions such as lattice constants, element size are considered to be much smaller than the wavelength of light that is interacting with a regular lattice of this kind of elements can be described by its effective permeability which is mu and that is also a function of the frequency so you can take it as $1 - \frac{A\omega^2}{\omega^2 - \omega_r^2 + i\Gamma\omega}$. So here what is this resonance frequency? This should be omega r.

So the resonance frequency omega r is basically omega naught epsilon sorry L sigma over L plus mu mu naught mu s square by 3L to the power minus half. So what are these terms? So if you can see here that the resonance frequency of individual element which is determined by its geometry that is where your design comes into the picture. Their concentration as well as their arrangement so all these things will decide what is omega naught and L is the self inductance. S is the effective cross section of these elements, mu is the concentration and r is the radius of the loop. So, these are the structural parameters that goes into this formula to decide what is the resonance frequency.



Reconfigurable Metamaterials

- The resonant frequency is determined by mutual interaction between the elements, which in most practically realizable cases is defined by:

$$L_\Sigma = L + \mu_o r \Sigma \qquad \text{(L27.3)}$$

where the lattice sum Σ can be calculated for a given geometry of elements and their arrangement through mutual inductance.

Figure: Schematic of the staggered lattice shift with a lateral displacement of every second metamaterial layer.

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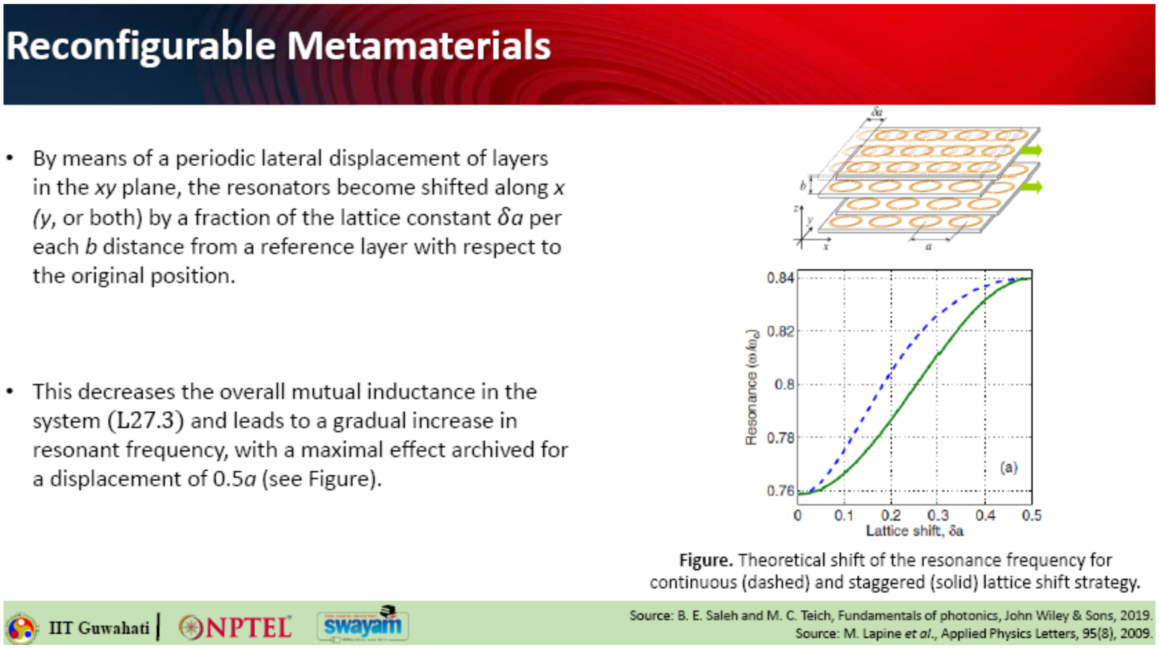
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: M. Lapine *et al.*, Applied Physics Letters, 95(8), 2009.

Now with that you can also see that resonance frequency is determined by the mutual interaction between the elements and which in most practically realizable cases can be defined as L sigma. What is L sigma? That is basically $L + \mu_o r \Sigma$. So this sigma is the lattice sum that actually tells you the sum over all the lattice points on which these elements are present. So here the lattice sum sigma can be calculated for a given geometry of elements and their arrangement through the mutual inductance. So that gives you a way to calculate the permeability.



Reconfigurable Metamaterials

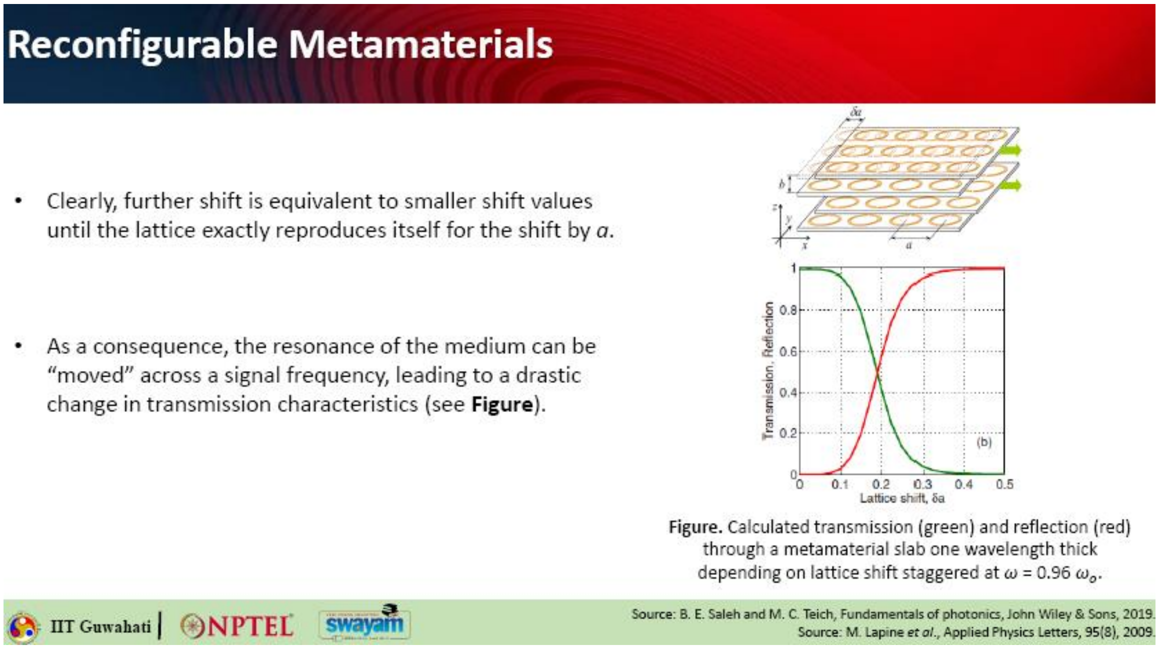
- By means of a periodic lateral displacement of layers in the *xy* plane, the resonators become shifted along *x* (*y*, or both) by a fraction of the lattice constant δa per each *b* distance from a reference layer with respect to the original position.
- This decreases the overall mutual inductance in the system (L27.3) and leads to a gradual increase in resonant frequency, with a maximal effect archived for a displacement of 0.5*a* (see Figure).

Figure. Theoretical shift of the resonance frequency for continuous (dashed) and staggered (solid) lattice shift strategy.

Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: M. Lapine *et al.*, Applied Physics Letters, 95(8), 2009.

By means of a periodic lateral displacement of layers in the xy-plane, so here is the xy-plane you can see, so you are actually doing the shifting in the lateral directions. So you can actually shift these resonators either along x or along y or along both x and y. And the amount of shift is basically delta lambda. And delta lambda can be given as you know delta, not delta lambda, delta a. And delta a per each b distance that is the separation between the two layers, that can be the way to represent this particular shift.

And when you see this and because of this shift if you plot the theoretical shift in the resonance frequency, so the continuous line shows the shift, it says continuous shift and the solid, so this one, the dashed line, the blue dashed line that you are seeing is basically for continuous lattice shift strategy. So you are just sliding it continuously and staggered one, solid one is for the staggered lattice shift. That means you are basically shifting it in a staggered fashion. So how it happens? So when you actually move the mutual, the shifting will actually take the resonator away from the you know axis. So initially they were all aligned you can assume and then you are sliding one of these intermediate layer, so that actually moves out.



Reconfigurable Metamaterials

- Clearly, further shift is equivalent to smaller shift values until the lattice exactly reproduces itself for the shift by *a*.
- As a consequence, the resonance of the medium can be “moved” across a signal frequency, leading to a drastic change in transmission characteristics (see **Figure**).

Figure. Calculated transmission (green) and reflection (red) through a metamaterial slab one wavelength thick depending on lattice shift staggered at $\omega = 0.96\ \omega_o$.

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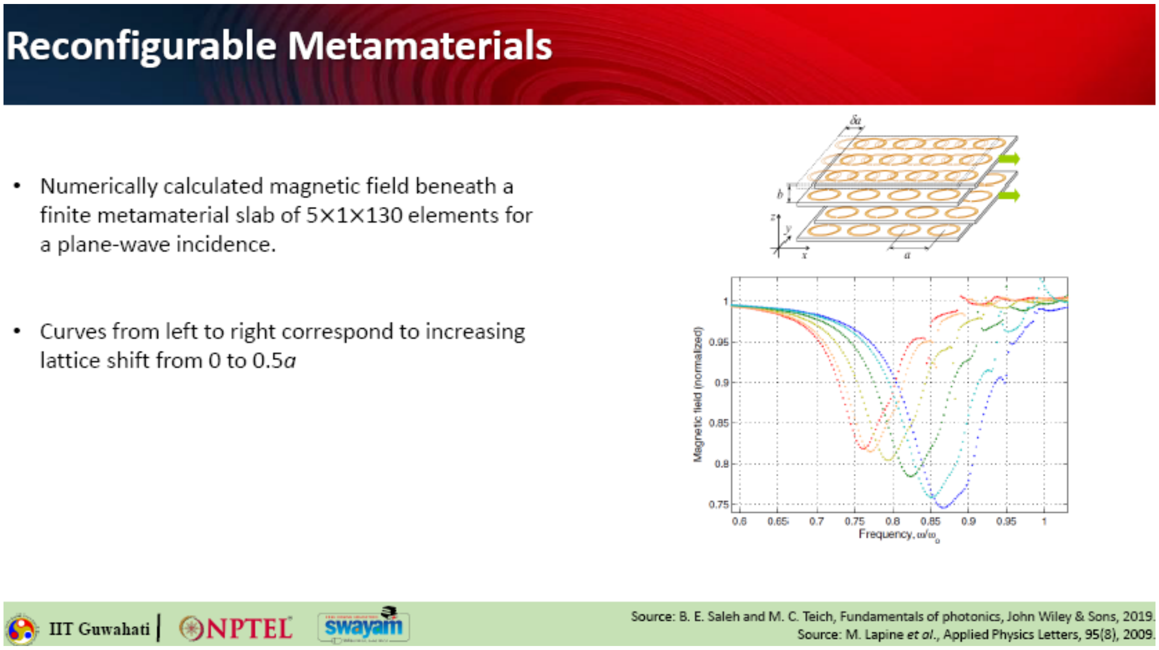
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: M. Lapine *et al.*, Applied Physics Letters, 95(8), 2009.

So this decreases the overall mutual inductance in the system and that will when L reduces there will be gradual increase in the resonant frequency. And that is what you are able to see that the resonant frequency which is normalized to omega naught is basically increasing as your shift is increasing. And then when the shift is half of the lattice period, it achieves the maximum value and then it will again follow the same pattern because it will just be repeating. So clearly any further shift will be equivalent to the smaller shift values until the lattice exactly reproduces itself for a shift by a. That is clearly understood that any shift by an amount of a will actually get back to the original position.

So you can only consider a shift up to 0.5 a. So what you have seen here is that because of this kind of shift the resonance of the medium has actually moved across the single frequency and that will bring a dramatic change in the reflection and the transmission characteristics of this metamaterial. So here you can see the calculated transmission curve the one in blue and the reflection curve is in red. So, this is calculated through a metamaterial slab which is one wavelength thick and it is dependent on the lattice shift that is staggered at omega equals 0.



Reconfigurable Metamaterials

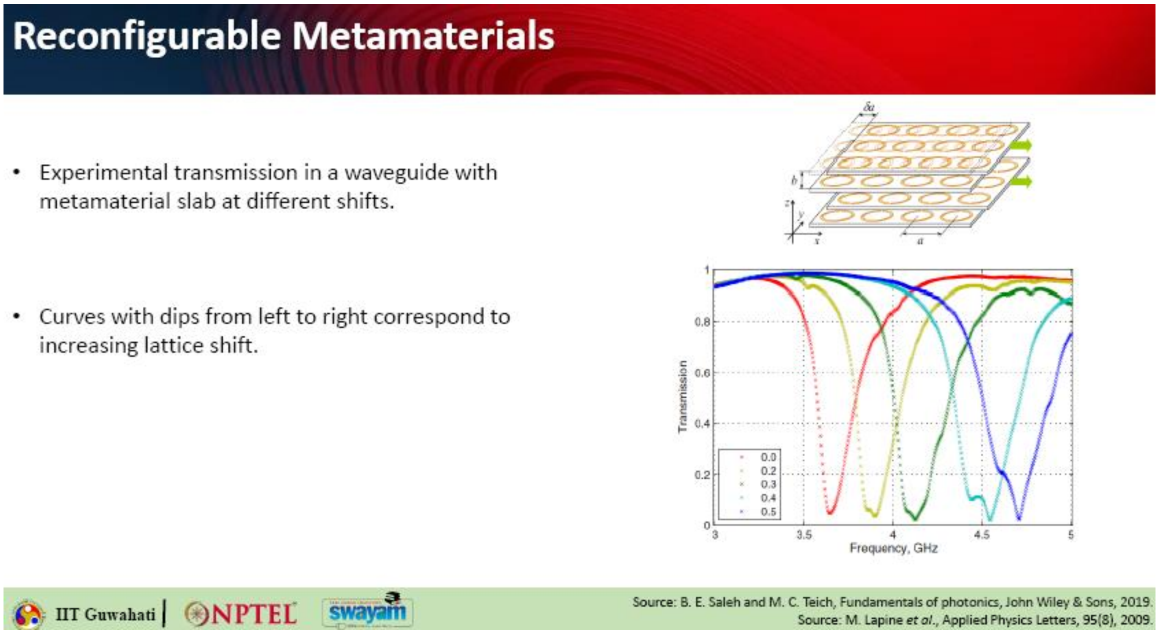
- Numerically calculated magnetic field beneath a finite metamaterial slab of 5×1×130 elements for a plane-wave incidence.
- Curves from left to right correspond to increasing lattice shift from 0 to 0.5*a*

Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: M. Lapine *et al.*, Applied Physics Letters, 95(8), 2009.

96 omega naught. So with staggered lattice shift you can see the reflectance and transmittance can be tuned. So this is something very very interesting as you can clearly see that from 0 to 1 you can switch. So what happens to transmission? The opposite trend happens in reflection. So the calculation here is basically shown for 5 x 1 x 130 elements. So that is the number of elements you have considered and you have also taken plane wave excitation and this gives you the magnetic field that is below this finite metamaterial slab and with the shift you can see the curves from left to right they correspond to a lattice shift of 0 to 0.

5 a. So you can see you can dramatically shift the resonance frequency by doing this kind of shift. So this was based on numerical calculation or numerical simulation. You can also do experiments and see the same effect. So these are basically the experimental transmission spectrum of a waveguide with this kind of metamaterial slab where you can tune the shift.

So this is the shift for 0, 0.2 a, 0.3 a, 0.4 a and 0.5 a and you can see how you are able to tune it. So that is how you can do the same metamaterial can be reconfigured to resonate at a different resonance frequency.



Reconfigurable Metamaterials

- Experimental transmission in a waveguide with metamaterial slab at different shifts.
- Curves with dips from left to right correspond to increasing lattice shift.

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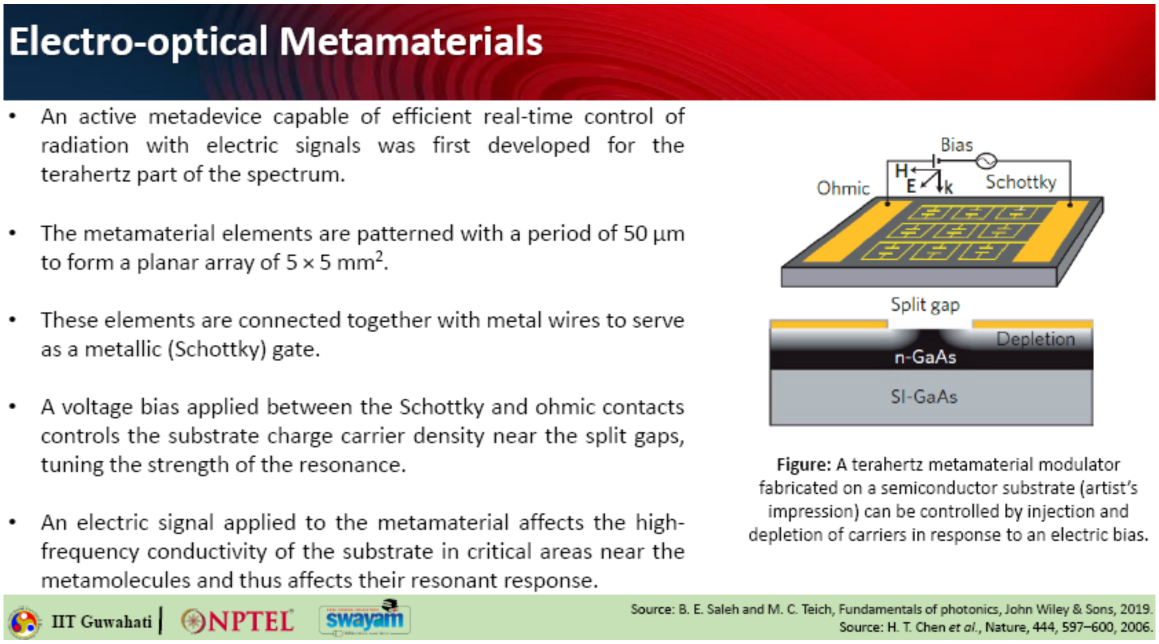
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: M. Lapine *et al.*, Applied Physics Letters, 95(8), 2009.

So that makes it a reconfigurable metamaterial. Now this kind of shifting of the lattice may be tricky when you are trying to do it in real time because there has to be some kind of arrangement to move these planes away and put them back or control that particular shift. So that is also possible by some kind of mechanical tuning of these shifts. There are other methods of tuning as well which are more popular that is giving rise to electro optical metamaterials. So here we are basically looking at a terahertz metamaterial modulator which is fabricated on a semiconductor substrate.



Electro-optical Metamaterials

- An active metadevice capable of efficient real-time control of radiation with electric signals was first developed for the terahertz part of the spectrum.
- The metamaterial elements are patterned with a period of 50 µm to form a planar array of 5 × 5 mm^2.
- These elements are connected together with metal wires to serve as a metallic (Schottky) gate.
- A voltage bias applied between the Schottky and ohmic contacts controls the substrate charge carrier density near the split gaps, tuning the strength of the resonance.
- An electric signal applied to the metamaterial affects the high-frequency conductivity of the substrate in critical areas near the metamolecules and thus affects their resonant response.

Figure: A terahertz metamaterial modulator fabricated on a semiconductor substrate (artist's impression) can be controlled by injection and depletion of carriers in response to an electric bias.

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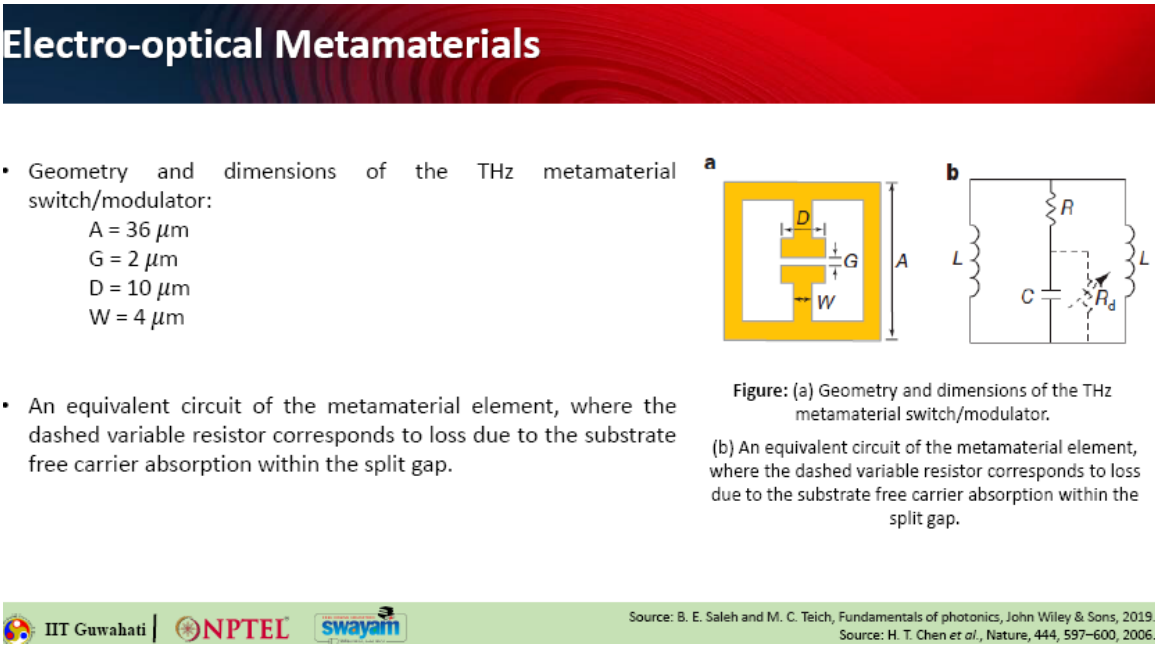
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

So this is not the actual diagram this is just a depiction of a schematic. So here the tuning is controlled by injection and depletion of carriers in response to electrical bias. So when you apply positive bias you can attract more electrons so that will be like injection of carriers so the conductivity changes that changes the permittivity of the underlying semiconductor region and then you change the optical response through it. And if you apply the opposite bias there will be depletion of carriers and that affects the optical response. So, these are examples of active meta device which are capable of efficient real-time control of radiation with electrical signals.



Electro-optical Metamaterials

- Geometry and dimensions of the THz metamaterial switch/modulator:
  - A = 36 μm
  - G = 2 μm
  - D = 10 μm
  - W = 4 μm
- An equivalent circuit of the metamaterial element, where the dashed variable resistor corresponds to loss due to the substrate free carrier absorption within the split gap.

Figure: (a) Geometry and dimensions of the THz metamaterial switch/modulator.

(b) An equivalent circuit of the metamaterial element, where the dashed variable resistor corresponds to loss due to the substrate free carrier absorption within the split gap.

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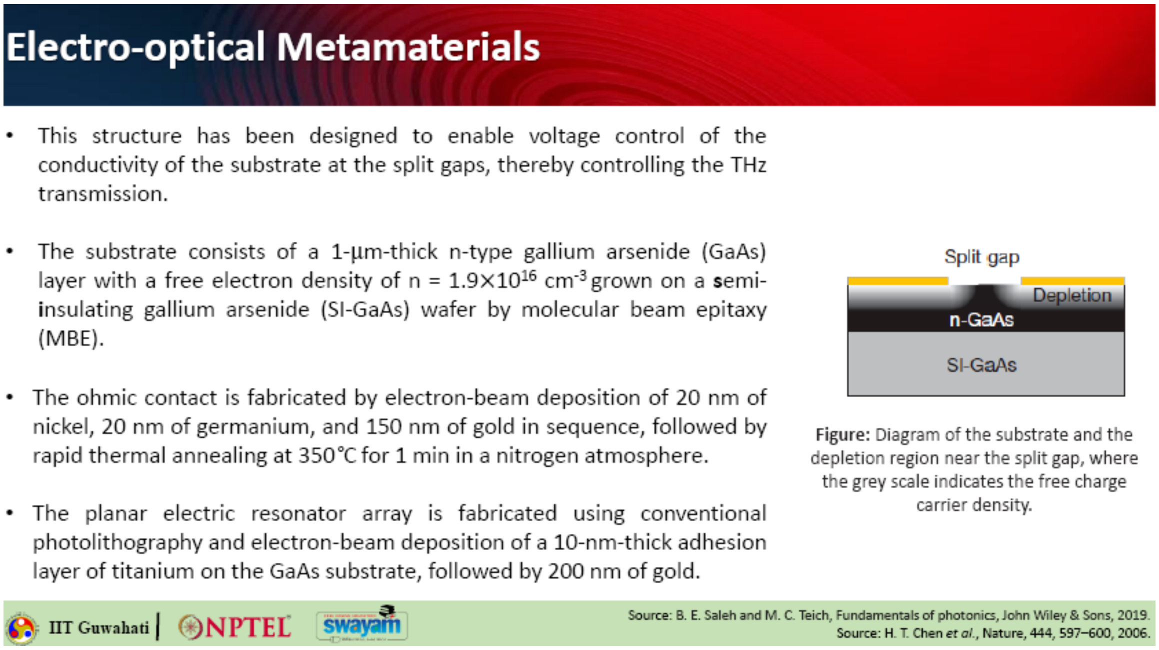
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

And these were first designed for the terahertz part of the spectrum. So here is an example of metamaterial elements of period 50 micron and they are actually forming a 5 cross 5 millimeter square planar array. So overall dimension is 5 mm by 5 mm. So this kind of a structure you can each pattern the period is actually 50 micron and these elements are all connected together through a metallic wire that you can see here there is a wire running. And these actually serve as Schottky gates.



Electro-optical Metamaterials

- This structure has been designed to enable voltage control of the conductivity of the substrate at the split gaps, thereby controlling the THz transmission.
- The substrate consists of a 1-µm-thick n-type gallium arsenide (GaAs) layer with a free electron density of n = 1.9×10^{16} cm^{-3} grown on a semi-insulating gallium arsenide (SI-GaAs) wafer by molecular beam epitaxy (MBE).
- The ohmic contact is fabricated by electron-beam deposition of 20 nm of nickel, 20 nm of germanium, and 150 nm of gold in sequence, followed by rapid thermal annealing at 350°C for 1 min in a nitrogen atmosphere.
- The planar electric resonator array is fabricated using conventional photolithography and electron-beam deposition of a 10-nm-thick adhesion layer of titanium on the GaAs substrate, followed by 200 nm of gold.

Figure: Diagram of the substrate and the depletion region near the split gap, where the grey scale indicates the free charge carrier density.

Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

And when there is a voltage applied between the Schottky and the ohmic contact that controls the substrate carrier charge density near the split gaps and that helps you in the tuning of the resonance as I mentioned here. So an electrical signal when it will be applied affects the high frequency conductivity of the substrate in the critical areas near these metamolecules mainly here in the gap region and that actually gives rise to the change in the optical properties. Now mind here that the orientation of the incident terahertz radiation is shown here. So the wave incident along this k vector then the magnetic field is polarized like this and the electric field is polarized in this particular direction. Now here is the dimension and actual geometry of the meta-atom that can be used for that terahertz meta-material switch or modulator whatever way you can use it.

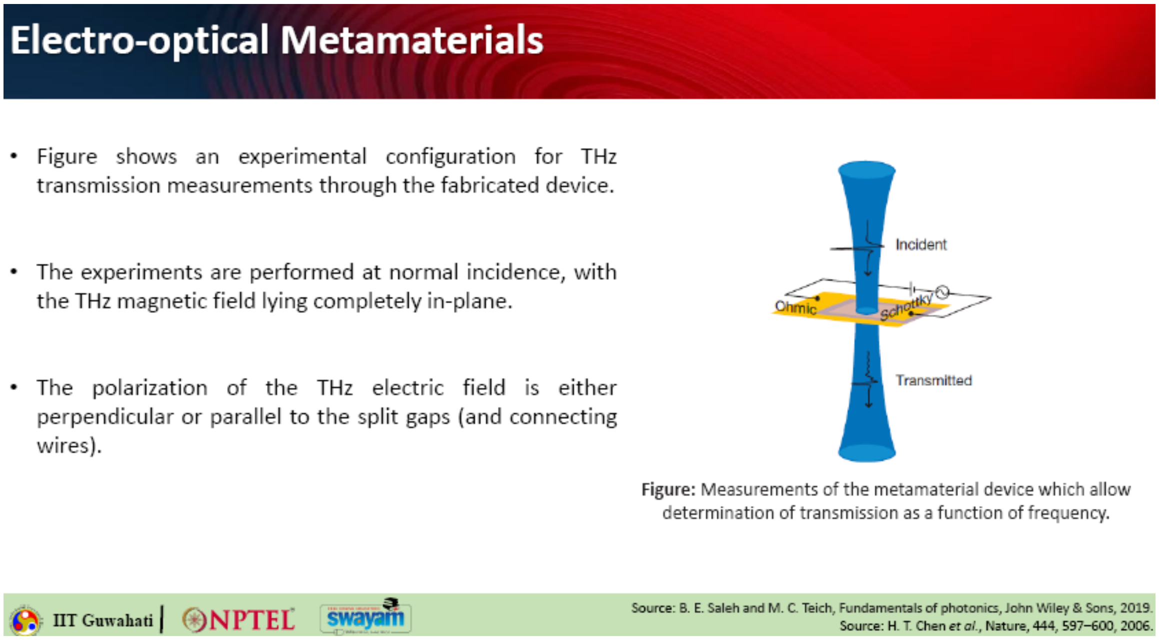
So here are the dimensions, this side is 36 micron, the gap is only 2 micron, the width of this region is 10 micron and this width is 4 micron. And you can also make an equivalent circuit model for this meta-material element. So the loop coils can be designed as a inductor, the gap can be modeled as a capacitor and the ohmic loss in this particular metallic structure can be modeled as a resistive element. So this is how typically you do. And there is another one, this one the dashed variable capacitor which is Rd and this corresponds to the loss due to the substrate free carrier absorption within the split gap and this is something can be tuned.

And the structure has been designed to enable voltage control of the conductivity of the substrate at this split gaps, thereby controlling the terahertz transmission. So if you look here, these gaps play a very important role. Now the substrate, now if you look at the substrate, the substrate actually consists of 1 micron thick n-type gallium arsenide, which has got a free electron density of 1.9 into 10 to the power 16 per centimeter cube. And that is grown on a semi-insulating that is SI, semi-insulating gallium arsenide wafer and this is done by molecular beam epitaxy method.

So we will look into this method towards the end of this course. Right now you just know about this method that is being used to grow this. The ohmic contact is fabricated by electron beam deposition of 20 nanometer of nickel, 20 nanometer of germanium and 150 nanometer of gold in sequence followed by rapid thermal annealing at 350 degree centigrade for 1 minute in nitrogen atmosphere. So this is the method of fabricating this particular ohmic contact. The planar electric resonator array is fabricated using conventional photolithography.

So that is how you actually made that periodic patterns. And then you have done electron beam deposition of 10 nanometer thick addition layer of titanium on the gallium arsenide substrate followed by 200 nanometer of gold. So this gold is basically patterned using photolithography to give you the desired structure of the metamaterial that you are seeing here. Now this is the experimental setup. So the experimental configuration for the terahertz transmission measurement.

So this is your device that has been fabricated and this will be the Schottky contact, this will be the ohmic contact, you are applying a bias across it. And you know it was conducted for normal incidence where the terahertz magnetic fields they were lying in plane and here you can see that the electric field can be either perpendicular or parallel to the split gaps and the connecting wire. So, there are two ways of having the electric field polarized.



Electro-optical Metamaterials

- Figure shows an experimental configuration for THz transmission measurements through the fabricated device.
- The experiments are performed at normal incidence, with the THz magnetic field lying completely in-plane.
- The polarization of the THz electric field is either perpendicular or parallel to the split gaps (and connecting wires).

Figure: Measurements of the metamaterial device which allow determination of transmission as a function of frequency.

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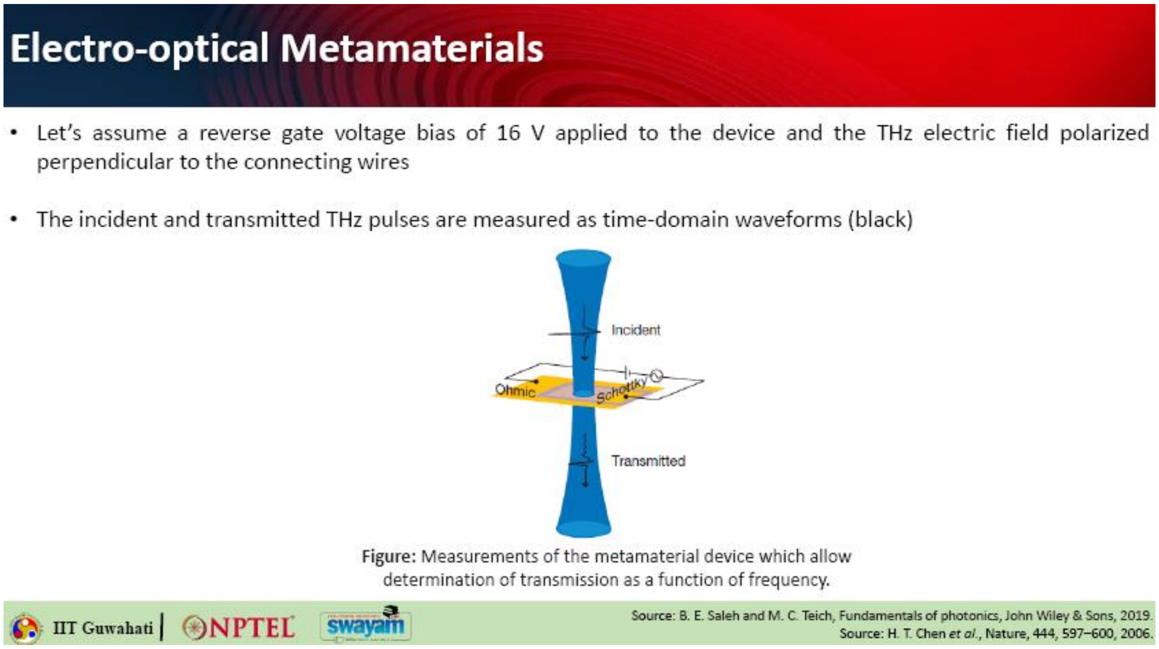
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

One can be perpendicular to the gap or parallel to the gap. Now let us assume a reverse bias gate voltage of 16 volt is applied to the device and the terahertz electric field is polarized perpendicular to the connecting wires. So, if you remember the connecting wires, those are connecting the different meta atoms or meta molecules.



Electro-optical Metamaterials

- Let's assume a reverse gate voltage bias of 16 V applied to the device and the THz electric field polarized perpendicular to the connecting wires
- The incident and transmitted THz pulses are measured as time-domain waveforms (black)

Figure: Measurements of the metamaterial device which allow determination of transmission as a function of frequency.

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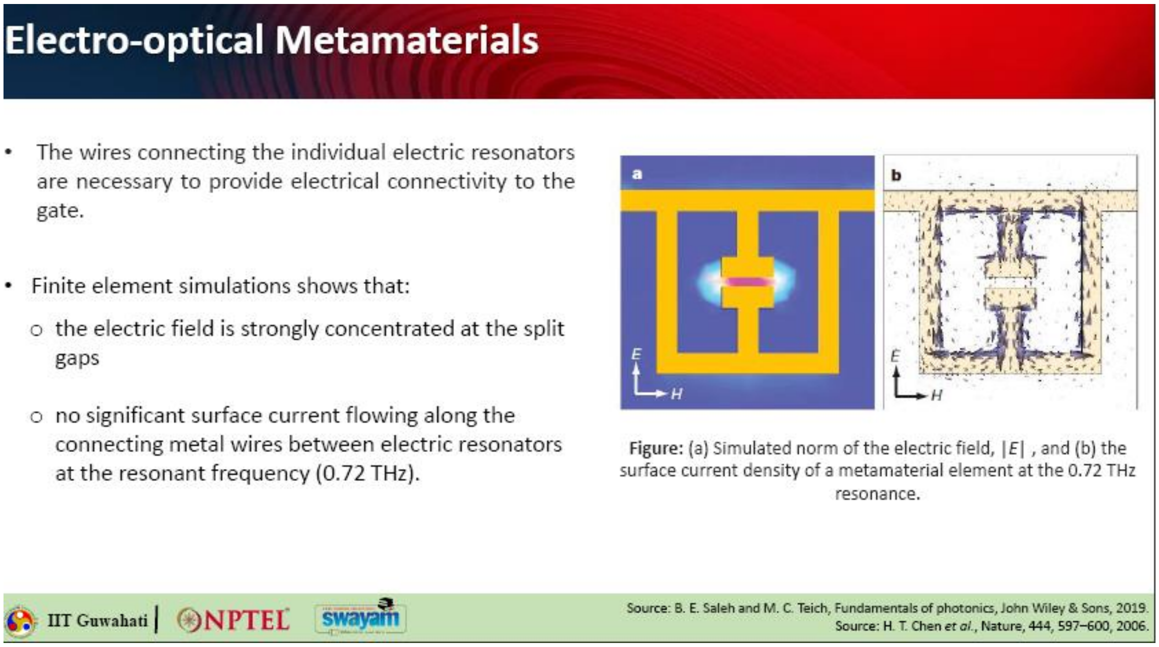
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

So, the electric field is considered to be perpendicular to that. And here the time domain waveforms in black, these are actually showing the incident and the transmitted terahertz pulses. So the wires which are connecting the individual electric resonators, they are actually providing electrical conductivity or electrical connectivity to the gate. The finite element method simulation that you have done, it shows that the electric field is strongly concentrated at the split gap.



Electro-optical Metamaterials

- The wires connecting the individual electric resonators are necessary to provide electrical connectivity to the gate.
- Finite element simulations shows that:
  - the electric field is strongly concentrated at the split gaps
  - no significant surface current flowing along the connecting metal wires between electric resonators at the resonant frequency (0.72 THz).

Figure: (a) Simulated norm of the electric field, $|E|$, and (b) the surface current density of a metamaterial element at the 0.72 THz resonance.

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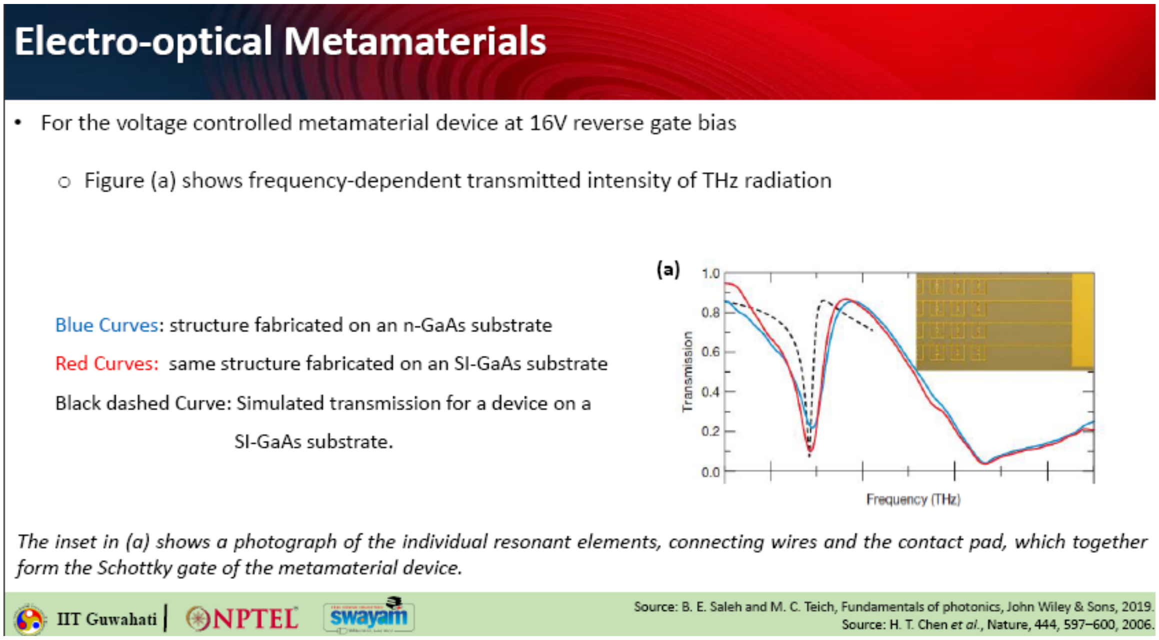
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

So this is where the electric field is mainly concentrated in the gap. And there is no significant current flowing along the connecting wire. So this is basically the plot of surface current density for that metamaterial element. So this is the connecting wire again. And here you can see the current is basically flowing like this in one loop and then like this opposite direction in another loop.



Electro-optical Metamaterials

- For the voltage controlled metamaterial device at 16V reverse gate bias
  - Figure (a) shows frequency-dependent transmitted intensity of THz radiation

Blue Curves: structure fabricated on an n-GaAs substrate
Red Curves: same structure fabricated on an SI-GaAs substrate
Black dashed Curve: Simulated transmission for a device on a SI-GaAs substrate.

The inset in (a) shows a photograph of the individual resonant elements, connecting wires and the contact pad, which together form the Schottky gate of the metamaterial device.

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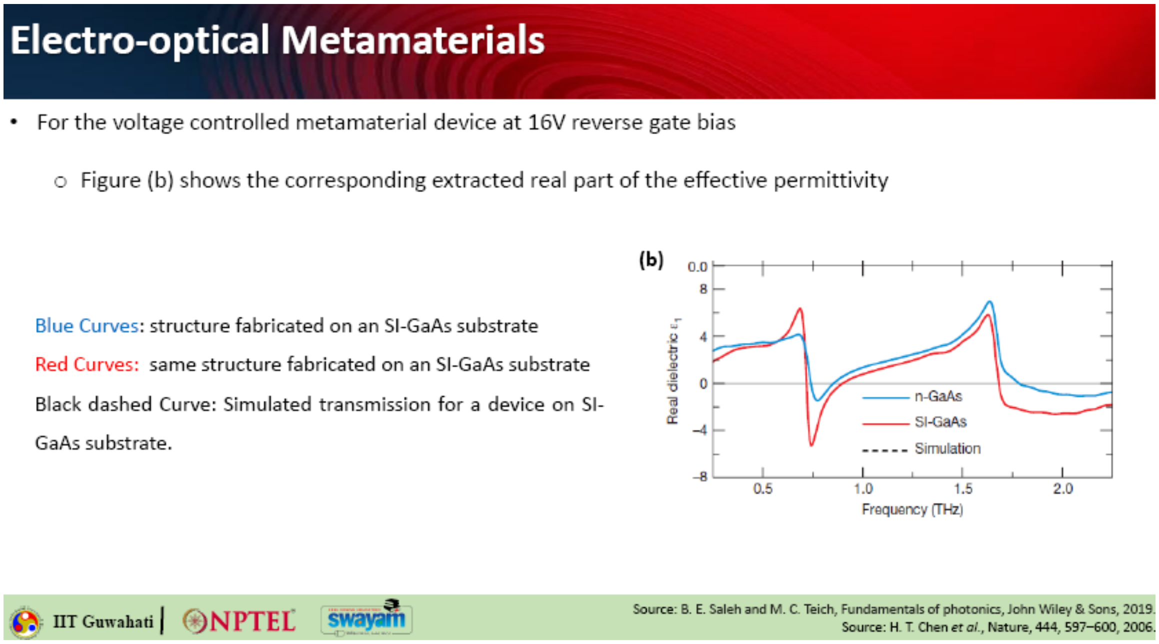
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

So what about the current flowing here, that is very very minimal. So you can say that no significant surface current is flowing along this connecting metallic wires between the electric resonators at the resonance frequency of 0.72 terahertz. Another important thing is that the two inductive loops that you see here, they are oppositely So one current goes in this direction and another current goes along this direction.

So they are basically oppositely wound. So you will see no response, magnetic response from this. So you will only get a net electric response from this kind of metamaterials. Now for the voltage controlled metamaterial device, so this is the device that as you can see this is the Schottky contact, these are the connecting wires and these are the elements and at 16 volt reverse gate bias, this particular plot shows you the transmission for the three different cases. Now what are those three cases? The blue curve that you see here, it is basically the structure that is fabricated on n-galeomer sonnet substrate. The red one is basically the same structure fabricated on that semi-insulating gallium arsenate substrate.



Electro-optical Metamaterials

- For the voltage controlled metamaterial device at 16V reverse gate bias
  - Figure (b) shows the corresponding extracted real part of the effective permittivity

Blue Curves: structure fabricated on an SI-GaAs substrate

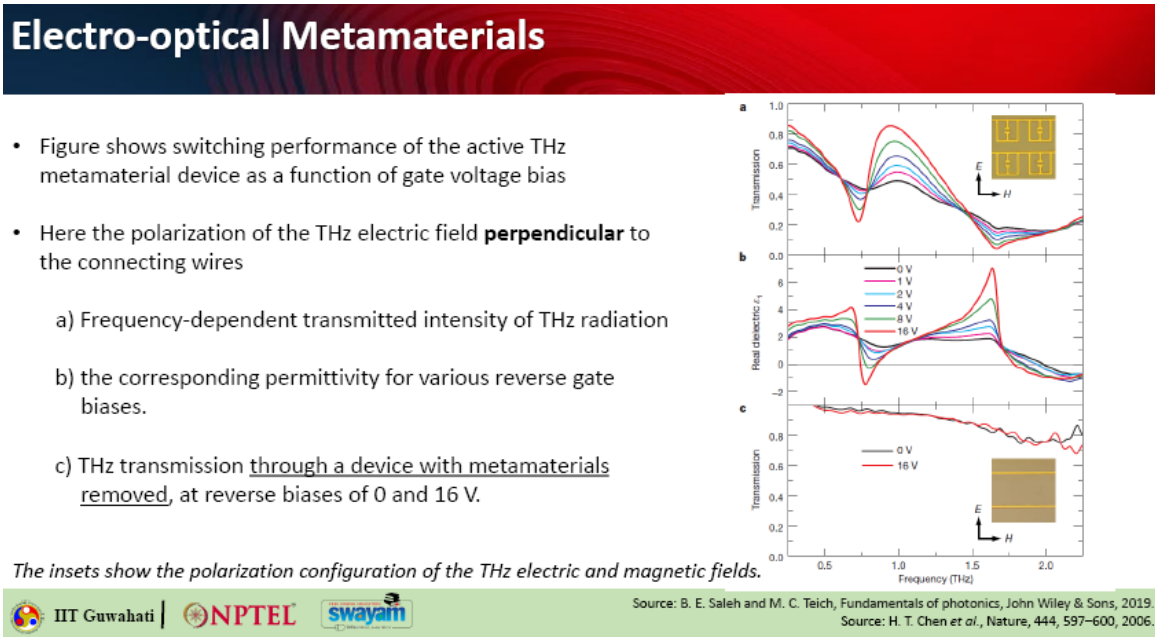
Red Curves: same structure fabricated on an SI-GaAs substrate

Black dashed Curve: Simulated transmission for a device on SI-GaAs substrate.

Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

And then the black dashed curve that you see here, it is basically the simulated version of the transmission curve. Now obviously in simulation you will see that all the elements are perfectly of the same size, the periodicity is uniform that is where the resonance is much more sharper, you get a higher Q when you actually get a simulated transmission spectrum. But in the case of fabricated devices the Q factor are like little lower because the peaks are or the dips that you can see here are wider. And the inset here shows the photograph of the individual resonating elements, the connecting wires and the contact pad which form the Schottky gate of this metamaterial device. Now after that you can also calculate what is the real part of the dielectric constant of that particular device.

So for the case of n-GaAS this is the blue curve and silicon, the red one is basically the semi-insulating gallium arsenate. The simulation part is not shown here. So how does this gives us tuning that let us see by applying different voltage biases. So those are the cases where we have seen what happens at 16 volt of reverse biasing. So now let us apply different bias voltages and measure the transmission as well as the dielectric permittivity.



Electro-optical Metamaterials

- Figure shows switching performance of the active THz metamaterial device as a function of gate voltage bias
- Here the polarization of the THz electric field **perpendicular** to the connecting wires

  a) Frequency-dependent transmitted intensity of THz radiation

  b) the corresponding permittivity for various reverse gate biases.

  c) THz transmission through a device with metamaterials removed, at reverse biases of 0 and 16 V.

The insets show the polarization configuration of the THz electric and magnetic fields.

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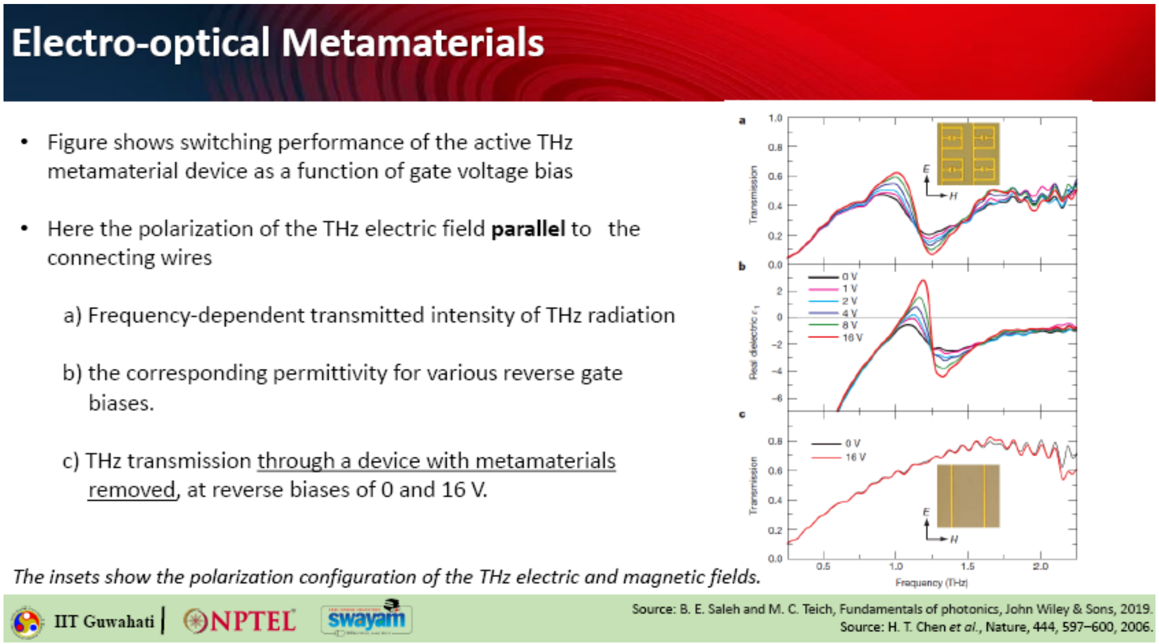
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

So here is a figure that shows the switching performance of the active terahertz metamaterial device as a function of gate bias voltage. So here the polarization of the terahertz electric field is considered to be perpendicular to the connecting wires. So these are the connecting wires and these are the electric field polarization direction. So this figure shows you the transmission which is frequency dependent transmission at different voltage levels. So, these are the different voltage levels and if you see why it has changed you can actually see that this is how the permittivity changes.



Electro-optical Metamaterials

- Figure shows switching performance of the active THz metamaterial device as a function of gate voltage bias
- Here the polarization of the THz electric field **parallel** to the connecting wires

  a) Frequency-dependent transmitted intensity of THz radiation

  b) the corresponding permittivity for various reverse gate biases.

  c) THz transmission through a device with metamaterials removed, at reverse biases of 0 and 16 V.

The insets show the polarization configuration of the THz electric and magnetic fields.

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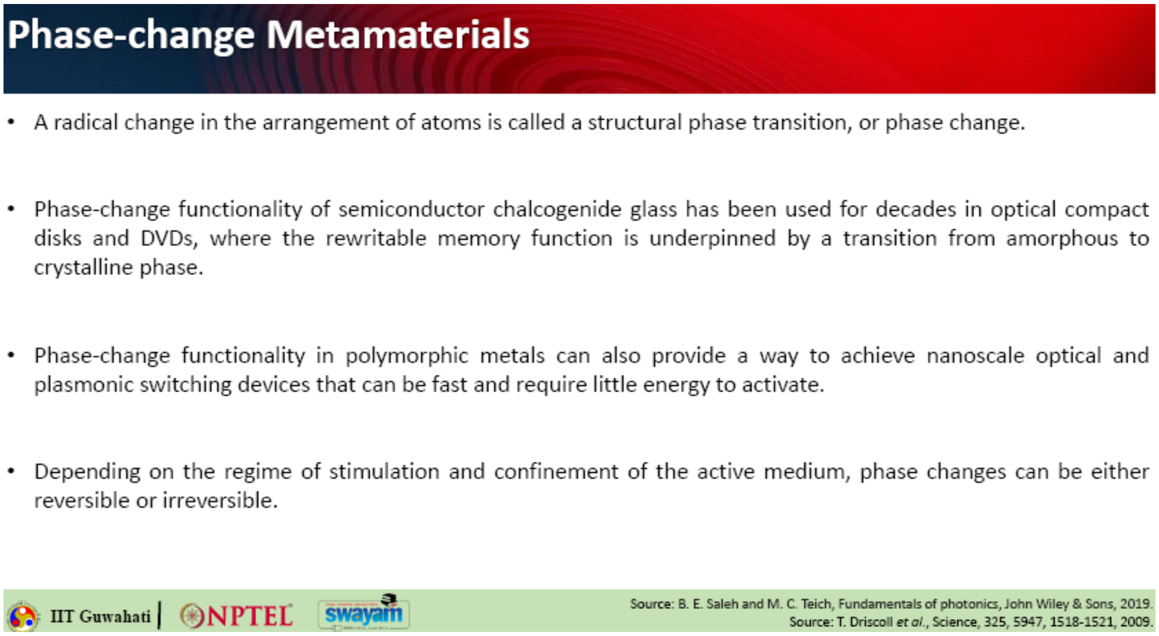
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: H. T. Chen *et al.*, Nature, 444, 597–600, 2006.

So at certain frequency range you can also see that this metamaterial is behaving like a metal. The real part of the dielectric becomes negative. And those are the cases where the transmission significantly drops because metal will be mostly reflective. In other cases it does go well.

Again when this part goes negative the transmission again drops. This is just a correlation but main point that I want to highlight here is that you are able to tune the transmission characteristics because you are able to tune the dielectric permittivity of this effective dielectric permittivity of this metamaterial structure. Now if you see the difference between 0 volt and 16 volt of the same structure without the metamaterials or with the metamaterials removed you will see that there is no difference. So there is no noticeable difference in the transmission curve. It means the main tunability is coming from this metamaterial structure.

So in both cases electric field patterns are shown here. So these are again those connecting wires. Only thing that is missing is this metamaterial elements. If you repeat the same experiment when the electric field is considered to be parallel of the connecting wires you see the tunability is not that drastically different. So you actually get more tunability when the electric field is perpendicular to this gap of the split gap. So here you see the tunability is much smaller as compared to the previous case.



Phase-change Metamaterials

- A radical change in the arrangement of atoms is called a structural phase transition, or phase change.
- Phase-change functionality of semiconductor chalcogenide glass has been used for decades in optical compact disks and DVDs, where the rewritable memory function is underpinned by a transition from amorphous to crystalline phase.
- Phase-change functionality in polymorphic metals can also provide a way to achieve nanoscale optical and plasmonic switching devices that can be fast and require little energy to activate.
- Depending on the regime of stimulation and confinement of the active medium, phase changes can be either reversible or irreversible.

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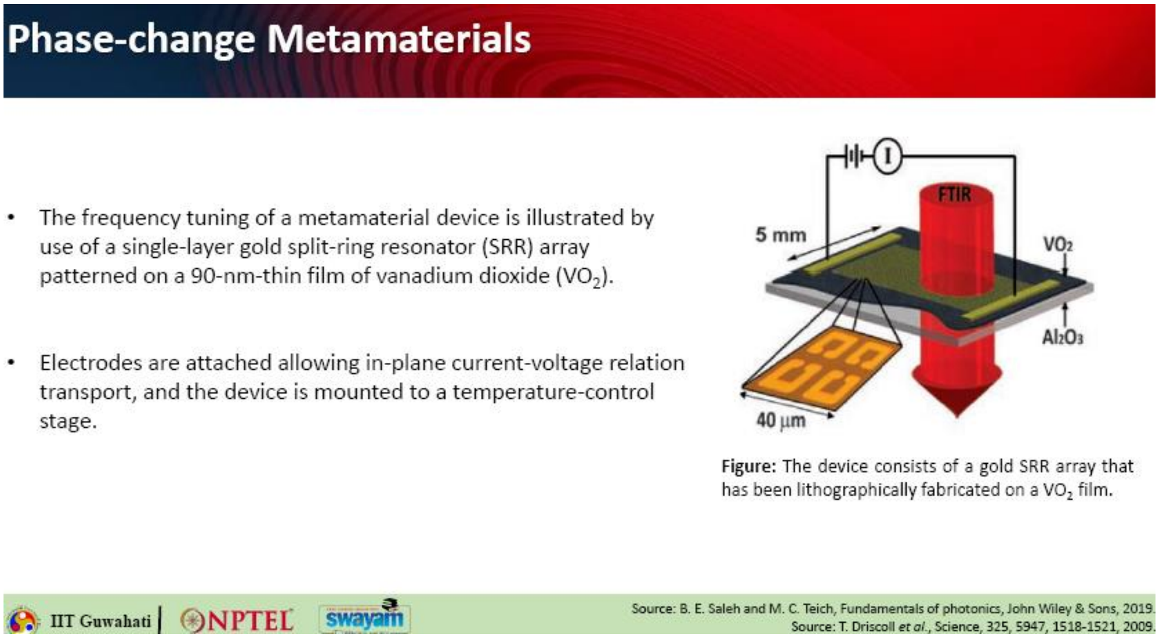
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: T. Driscoll *et al.*, Science, 325, 5947, 1518-1521, 2009.

Similarly the real part of the dielectric constant is also less tunable. And this is the case where you are redoing the experiment between calculation between 0 volt and 16 volt and you see no difference when the metamaterial elements are not present. So this quickly gives us an overview that we can use electrical biasing to get charge carriers below your split gap and you are able to change the capacitance and that actually change the resonance frequency that changes the effective permittivity and that is how the overall effect of this metamaterial can be tuned. There are other types of metamaterials which are reconfigurable that is based on different kind of phase change materials. So we look into those kind of metamaterial structures now. So, a radical change in the arrangement of atoms is basically called a structural phase change or you can simply called a phase change or phase transition.

Now phase change functionality of semiconductor chalcogenide plus has been used for decades in optical compactive discs that is CD or DVDs where the rewritable memory function is basically underpinned by a transition from amorphous to crystalline phase. So these are basically concepts from material science but they are very important to make optical storage and devices. So in material science polymorphism is basically a property where a solid material can exist in more than one crystal structure. So, polymorphism is basically a form of isomerism.



Phase-change Metamaterials

- The frequency tuning of a metamaterial device is illustrated by use of a single-layer gold split-ring resonator (SRR) array patterned on a 90-nm-thin film of vanadium dioxide (VO_2).
- Electrodes are attached allowing in-plane current-voltage relation transport, and the device is mounted to a temperature-control stage.

Figure: The device consists of a gold SRR array that has been lithographically fabricated on a VO_2 film.

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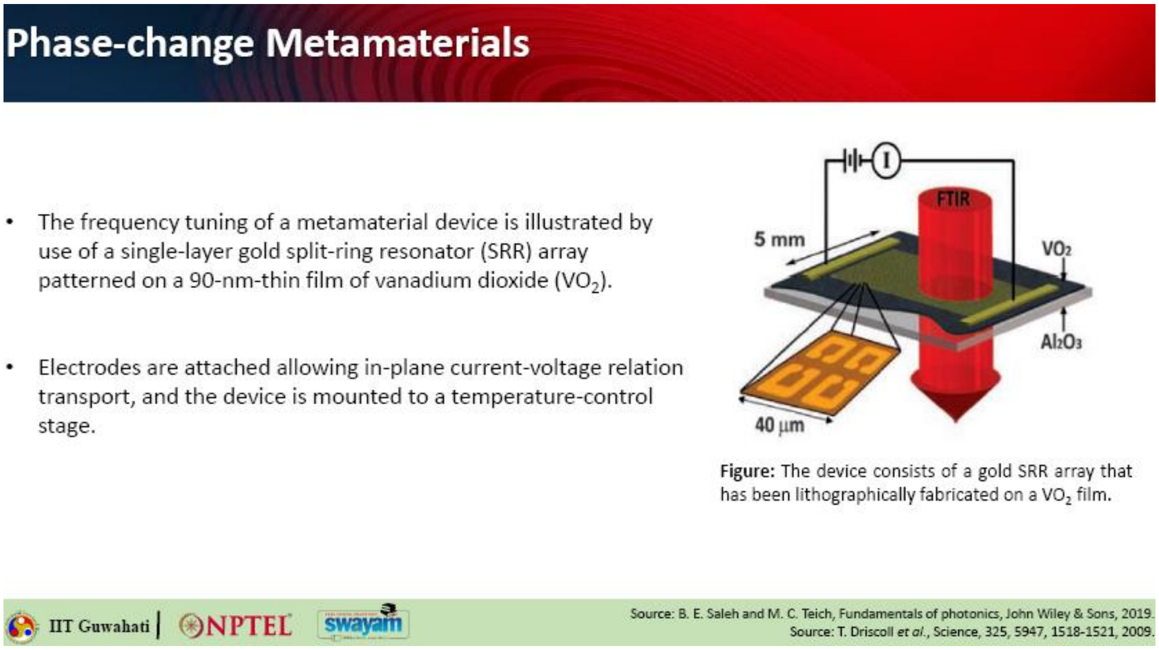
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: T. Driscoll *et al.*, Science, 325, 5947, 1518-1521, 2009.

So any crystalline material can exhibit this particular phenomena. So when we discuss about phase change functionality in polymorphic materials that can give a way to achieve nanoscale optical and plasmonic switching devices that can be fast and they will require very less energy to activate. And this is what we are looking for we are actually looking for fast and quick tuning options. So depending on the regime of stimulation and confinement of the active medium phase change can be either reversible or irreversible. So let us look into one such particular device. So here what is shown you have got a gold split ring resonator array which has been lithographically fabricated on a VO_2 vanadium dioxide film that is on a alumina substrate.

And the thickness of the vanadium dioxide film is 90 nanometer and you can apply now current between these two electrodes that you see here. And you can have illumination in this particular direction and there will be change in the optical transmission spectrum.

So the electrodes that you see here they are attached allowing in-plane current voltage relation transport and the device is basically mounted on a temperature control stage. Now VO_2 will change its phase from an insulating to metal depending on the temperature.



Phase-change Metamaterials

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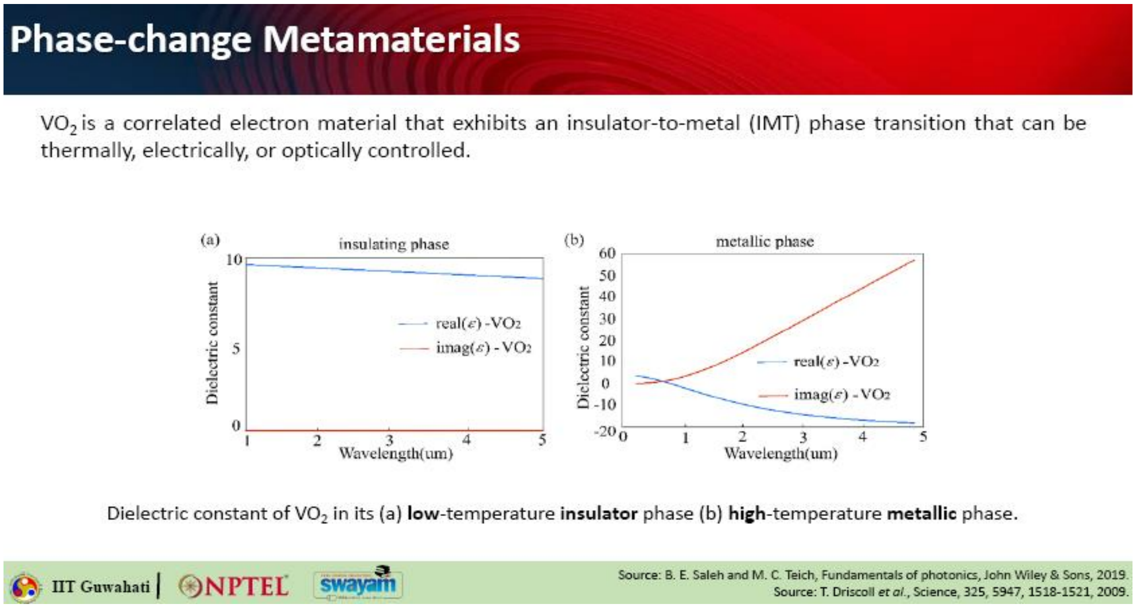
Source: T. Driscoll *et al.*, Science, 325, 5947, 1518-1521, 2009.

So, the transition temperature is typically 68 degrees that we will see quickly. So here we understand that VO2 is basically a correlated electron material that exhibits an insulated to metal phase transition and this can be activated thermally electrically or optically. So what happens when it is in insulating state phase? So, this is the case when now the VO_2 is an insulator so it is typically the low temperature phase of VO_2. You see the real part is the dielectric constants real part is positive and the imaginary part is negative sorry is 0. So, this is like a typical insulator and after the transition phase transition that is at high temperature VO_2 goes into metallic stage. So there you can see that the real part is basically negative so it behaves like metal and it is also a lossy metal so there is a loss associated.

So the same material can behave like a insulator before the transition phase transition temperature and it can behave like a metal beyond the phase transition temperature. So VO_2 basically shows a phase transition of a percolative nature in which 5 to 10 nanometer metallic puddles emerge and grow in the insulating host. So this is how it is like this is how the phase transition take place. It has attracted considerable attention as an active medium for hybrid metamaterial structures. Hybridizing vanadium dioxide with metamaterial shows around 20% temperature activated tuning in the transmission spectrum within the terahertz range that is pretty good 20% tuning capability and a form of electrically activated memory function and persistent frequency tuning of a metamaterial can be obtained which allows lasting modification of its response by using simultaneous stimulus have also been demonstrated.



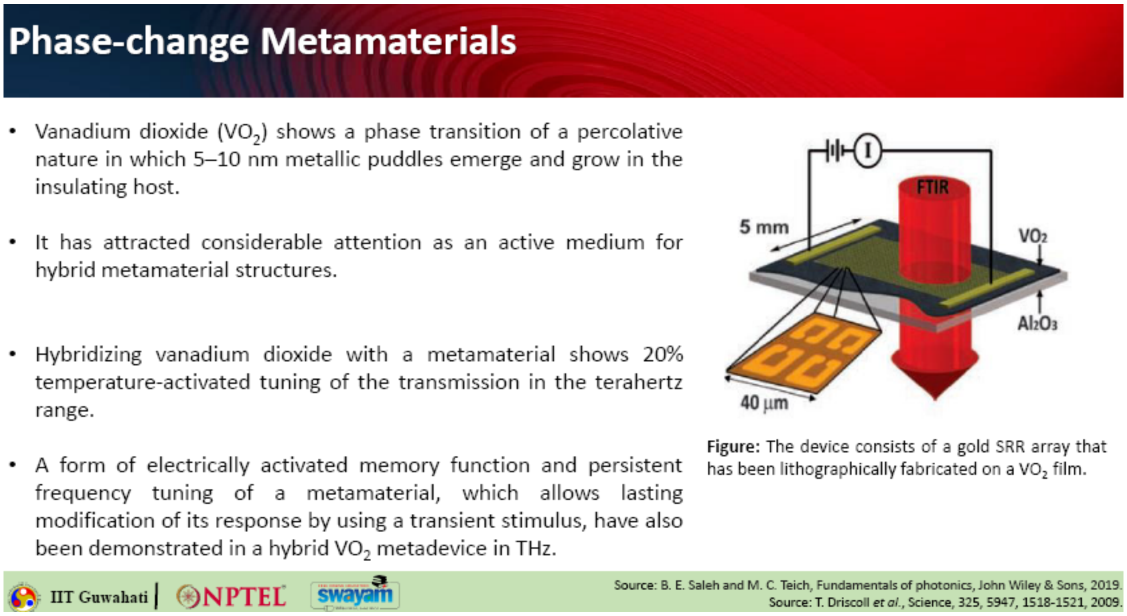
Phase-change Metamaterials

VO_2 is a correlated electron material that exhibits an insulator-to-metal (IMT) phase transition that can be thermally, electrically, or optically controlled.

Dielectric constant of VO_2 in its (a) **low**-temperature **insulator** phase (b) **high**-temperature **metallic** phase.

Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: T. Driscoll *et al.*, Science, 325, 5947, 1518-1521, 2009.

So all these demonstration of hybrid VO_2 meta devices they have been done in the terahertz range. So, this insulated to metal transition that happens in VO_2 is highly hysteretic and exhibits memory effects. So you can see here that this is the temperature scale and this is the DC resistance scale. So this shows the simultaneous DC transport and far infrared probing. So, this is also giving you the split ring resonator resonance frequency of a metamaterial where VO_2 has been used as a supporting material and that goes through the phase transition. So, this is the axis where temperature is increasing. So you can start like this and you can go increase increase and this particular vertical line the dashed line that you see here this is basically the phase transition point. So beyond which VO_2 will change from insulated to metal. So, this phase transition also affects the dielectric properties of the VO_2 in a specific way. So, at the onset of this transition electronic correlations acting in concert with the spatial inhomogeneity of VO_2 create a rapidly divergent permittivity.



Phase-change Metamaterials

- Vanadium dioxide (VO_2) shows a phase transition of a percolative nature in which 5–10 nm metallic puddles emerge and grow in the insulating host.
- It has attracted considerable attention as an active medium for hybrid metamaterial structures.
- Hybridizing vanadium dioxide with a metamaterial shows 20% temperature-activated tuning of the transmission in the terahertz range.
- A form of electrically activated memory function and persistent frequency tuning of a metamaterial, which allows lasting modification of its response by using a transient stimulus, have also been demonstrated in a hybrid VO_2 metadevice in THz.

Figure: The device consists of a gold SRR array that has been lithographically fabricated on a VO_2 film.

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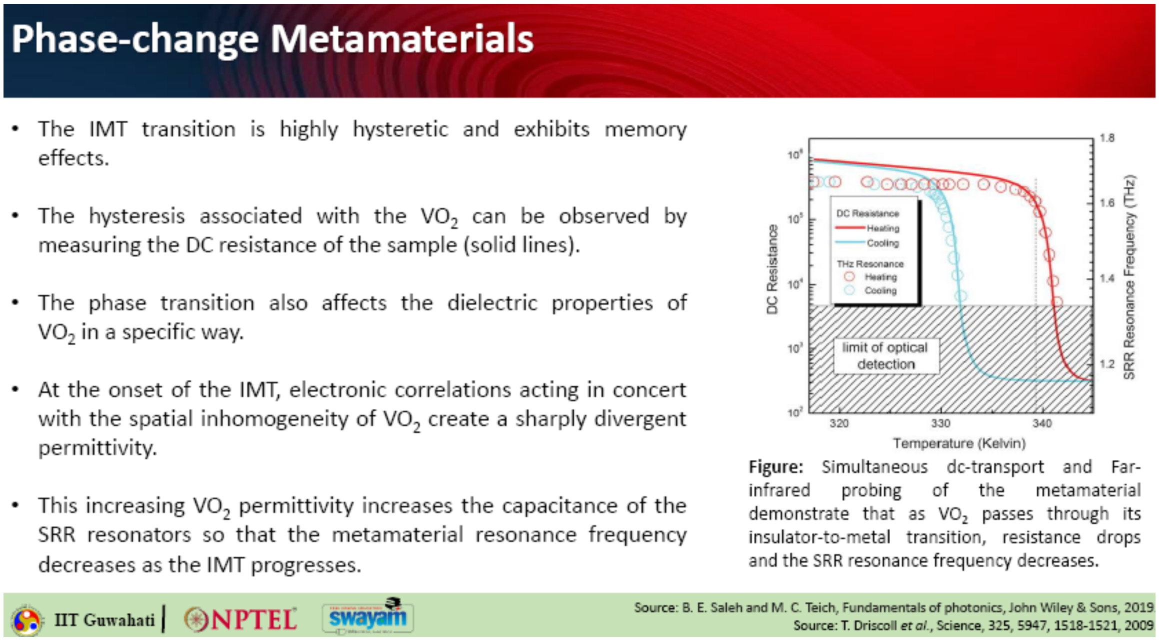
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: T. Driscoll *et al.*, Science, 325, 5947, 1518-1521, 2009.

So here you see the DC resistance significantly drops. And this is how it creates a kind of hysteresis because when you come back from this point it does not follow the same path rather it follows like this and then it goes back here. So this is the hysteresis so this the red one is the heating cycle and the blue one is the cooling cycle. So along the red line it will when you heat it this is how the DC conductive or DC resistance will change. The circles are basically giving you the resonance frequency you can see here terahertz resonance.



Phase-change Metamaterials

- The IMT transition is highly hysteretic and exhibits memory effects.
- The hysteresis associated with the VO_2 can be observed by measuring the DC resistance of the sample (solid lines).
- The phase transition also affects the dielectric properties of VO_2 in a specific way.
- At the onset of the IMT, electronic correlations acting in concert with the spatial inhomogeneity of VO_2 create a sharply divergent permittivity.
- This increasing VO_2 permittivity increases the capacitance of the SRR resonators so that the metamaterial resonance frequency decreases as the IMT progresses.

Figure: Simultaneous dc-transport and Far-infrared probing of the metamaterial demonstrate that as VO_2 passes through its insulator-to-metal transition, resistance drops and the SRR resonance frequency decreases.

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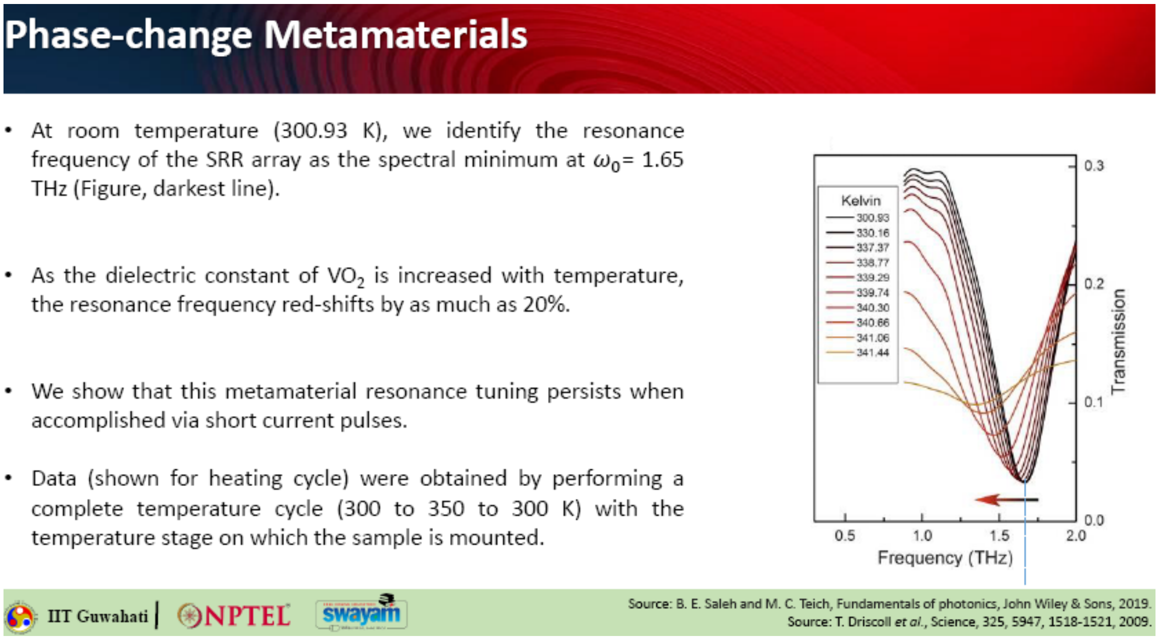
Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019
Source: T. Driscoll *et al.*, Science, 325, 5947, 1518-1521, 2009

The red circles are for heating cycle, blue circles are for cooling cycles. And this is the region where there is some limit of optical detection because of the fundamental limitations. So you do not have any other detection below this area that is why there are no measurement taken below this. But here what you can see that when the conduct on the resistance significantly drops this there will be change in the VO_2 permittivity. So, this when VO_2 permittivity increases this increases the capacitance and when the capacitance will increase the resonance frequency will decrease.

So this is the reason why you are seeing the drop in the resonance frequency. So this is the frequency scale the resonance frequency drops when this transition progresses. Now here is another plot which also tells you about the heating cycle. So at room temperature you can see this is basically the resonance frequency and this is the transmission graph. So here you can see that at room temperature that is the black curve 300.

93 Kelvin you see the black curve it has got a dip here so the resonance is around 1.65 terahertz ok and as you keep on increasing the temperature of the VO_2 ok. So in that case what is happening you are increasing the temperature so you are moving along the heating line and you see the resonance frequency is reducing right and this is what you see here. So as the dielectric constant of the VO_2 increases with temperature the resonance frequency red shifts ok. The frequency decreases means wavelength will go towards larger wavelength so it is called a red shift and the amount of red shift is as much as 20 percent and which is pretty pretty good ok. So, we show that this metamaterial response tuning persist when accomplished via short current pulses.



Phase-change Metamaterials

- At room temperature (300.93 K), we identify the resonance frequency of the SRR array as the spectral minimum at ω_0= 1.65 THz (Figure, darkest line).
- As the dielectric constant of VO_2 is increased with temperature, the resonance frequency red-shifts by as much as 20%.
- We show that this metamaterial resonance tuning persists when accomplished via short current pulses.
- Data (shown for heating cycle) were obtained by performing a complete temperature cycle (300 to 350 to 300 K) with the temperature stage on which the sample is mounted.

Source: B. E. Saleh and M. C. Teich, Fundamentals of photonics, John Wiley & Sons, 2019.
Source: T. Driscoll *et al.*, Science, 325, 5947, 1518-1521, 2009.

So you can send short current pulses and that will do this kind of temperature heating. So VO_2 heating will take place and you can actually change the transmission spectrum. So here as I mentioned we have shown the heating cycle but it was actually done by performing the experiment over the complete temperature cycle that is you start with 300 you go to 350 and then you go back to 300 again ok with a temperature stage on which the sample the VO_2 sample along with the metamaterial was mounted. So here the main objective was to tell you that there are ways of making your metamaterial devices actively tunable. That means you actually fabricate your metamaterial but then you put it on some material where with some external stimulus like current or heat or optically you are able to change its property and that change in the property will affect the resonance of the metamaterials and why that will happen because the metamaterials if you look for some gaps like capacitance in a split resonator ok.

The capacitance basically depends on the permittivity of the material that is in that gap ok. So those kind of thing actually helps you. So if you are able to change the permittivity by keeping the area and the thickness of the gap same you are actually able to change the capacitance and once you are able to change the capacitance you can change the resonance frequency. So this is the way you can actively tune the resonance of the metamaterials and that makes your metamaterial reconfigurable. So with that we will stop here and in the next lecture we will start discussing about metasurfaces and frequency selective surfaces. So if you have got any queries on this particular lecture you can drop an email to me at this particular email address mentioning the lecture slide as well as MOOC on the subject line. Thank you.