Course Name: Introduction to Microwave and Optical Metamaterials
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Week-12
Lecture-56

Lec 56: Tunable Metamaterials-based Sensors

Hello everyone, welcome to Lecture 56 of the online course on Introduction to Microwave and Optical Metamaterials. Today's lecture will be on tunable metamaterial-based sensors.

Lecture Outline

- Challenge of Conventional Sensors
- Tunable Metamaterials-based Sensors
  - Introduction
    - Sensing Principle using Tunable Metamaterials
    - Refractive Index Sensing using Metamaterial
  - Tunable MM-based biosensors in the GHz/Microwave Domain
    - Tunable High-Q Metamaterial based Temperature Sensing
  - Tunable MM-based biosensors in Optical frequency Domain
    - Tunable Infrared Metamaterial-based Biosensor

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Here is the lecture outline. We will first discuss the challenges of conventional sensors and then we will focus on tunable metamaterial-based sensors. With an introduction to the sensing principle using tunable metamaterials, we will discuss refractive index sensing using metamaterials. Then we will look into tunable metamaterial-based biosensors in the gigahertz and microwave domains.

We will take up some examples of tunable high Q metamaterial-based temperature sensing and then We will also take up one example from the optical frequency domain where we will discuss a tunable infrared metamaterial-based biosensor.

Challenge of Conventional Sensors

- **Fixed Performance:** Many traditional sensors have a fixed operating frequency and sensitivity.
- **Environmental Interference:** They can be susceptible to noise and interference, impacting accuracy.
- **Limited Scope:** A single sensor may not be ideal for detecting a wide range of analytes or for different conditions.
- **Need for Active Control:** We need sensors that can adapt to their environment and the properties of the sample being measured.

Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021

So, let us first focus on the challenges of conventional sensors. First of all, their performance is typically fixed because they have a fixed operating frequency and sensitivity. Then the conventional sensors have environmental interference, which means They are susceptible to noise and interference that impact their accuracy.

Moreover, the scope of a conventional sensor is limited because a single sensor will not be ideal. For detecting a wide range of analytes or different operating conditions. And then we need sensors that can address this kind of problem; you can understand that there is a need for active control. That means we need sensors that can adapt to their environment and the properties of the sample that are being measured.

So, with that, we introduce metamaterial-based sensors.

Introduction

- **Metamaterials (MMs)**:
  - Artificially engineered structures with subwavelength unit cells
  - Briefly recap that EM response in MMs determined by their structure, not just their composition.

- **Tunable Metamaterials**:
  - MMs integrate active materials whose EM properties can be dynamically reconfigured
  - Enable multi-functional and reconfigurable device performance.

- **Importance in Sensing**:
  - Enhanced sensitivity via strong field confinement and resonant effects
  - Real-time adaptability to different analytes and environmental changes
  - Applications: biochemical detection, environmental monitoring, IR spectroscopy, and wearable sensors.

- Combination of metamaterial resonance selectivity + tunability → Ultra-sensitive, versatile sensing platforms.

Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021

All of you know that metamaterials are basically artificially engineered structures with subwavelength unit cells and a quick recap of this is that the electromagnetic property The response of these metamaterials is determined by their structure, not their chemical composition, right? So, when you talk about tunable metamaterials, that means these metamaterials basically integrate some active materials. whose electromagnetic properties can be dynamically reconfigured. So, you can think of stimulus like thermal something like phase change materials or electrical that is Where you can give some bias control, something like in liquid crystals or graphene, or you can think of it mechanically. Something like MEMS-based geometry change, okay.

So, this kind of thing will give you multifunctional and reconfigurable device performance. So, why are they important in sensing? Because of advanced sensitivity via strong field confinement. And resonant effects will basically improve the sensitivity and detection of the analytes, right? Real-time adaptability is also very important, as it allows you to cater to different analytes and environmental changes. So, the typical applications could be in biochemical detection, environmental monitoring, IR spectroscopy, and wearable sensors. So, combination of metamaterials, resonance selectivity and tunability can give rise to ultra sensitive versatile sensing platforms.

Introduction

- Materials & Tuning Strategies
  - **Liquid Crystals (LCs)**
    - ✓ Electric field alters permittivity → adjustable resonance in metamaterials based devices.
  - **Micro-Electro-Mechanical Systems (MEMS)**
    - ✓ Electrothermal/Electrostatic actuation enables structural reconfiguration of metamaterials.
  - **Phase-Change Materials (PCMs)**
    - ✓ VO_2, paraffin wax: Temperature-driven phase transitions
    - ✓ GST: Suitable for thermal sensing and switchable absorber applications.

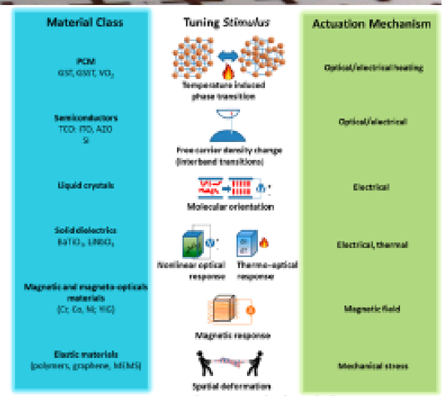

Figure: Principal tuning methods with the class of related materials

- Sensing Mechanisms using Tunable Metamaterials
  - **Refractive-Index Sensing :** Resonance frequency shifts with changes in the analyte's refractive index.
  - **Dynamic Control :** Active tuning with the use of active stimuli like MEMS, thermal, or liquid crystals
    - ✓ Enables rapid reconfiguration for multi-functional sensing.

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Source: Choudhury, Pankaj K., ed. *"Metamaterials: technology and applications"* CRC Press, 2021

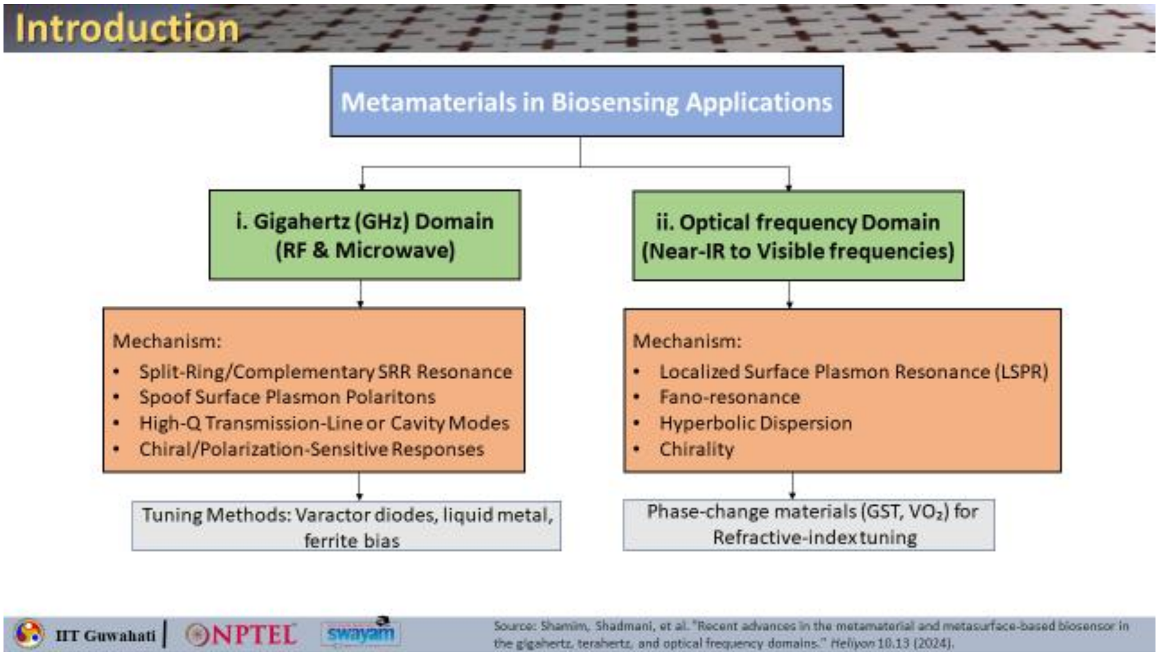
So, there could be different tuning mechanisms. So, you can actually look into this principal figure that tells you about phase change materials, something like GST or VO2, where you can actually have optical or electrical heating that acts as a stimulus and changes the property. You can think of semiconductors as transparent conducting oxides like ITO, AZO, or silicon, where you can have optical or electrical pumping. There, the free carrier density will change, and that basically changes the interband transition and the electrical or optical properties.

You can think of liquid crystals where electrical biasing can change the molecular orientation, and you can achieve tunability. You can also think of solid dielectrics like barium titanate or lithium niobate, which are giving a non-linear optical response. or thermo-optical response based on electrical and thermal biasing or pumping. There are other kinds of materials that are also sensitive to magnetic fields. And then there are materials that are sensitive to mechanical stress, such as polymers, graphene, or MEMS.

which can undergo special deformation to give you a tunable property. So, of these, a couple of popular ones are liquid crystals or microelectromechanical systems, or MEMS or phase change materials which are basically showing this one basically showing temperature driven phase transitions, right. There is another material called GST. So, that is also suitable for thermal sensing and switchable absorber applications. So, with that we can think of different sensing mechanisms where you can apply tunable metamaterials.

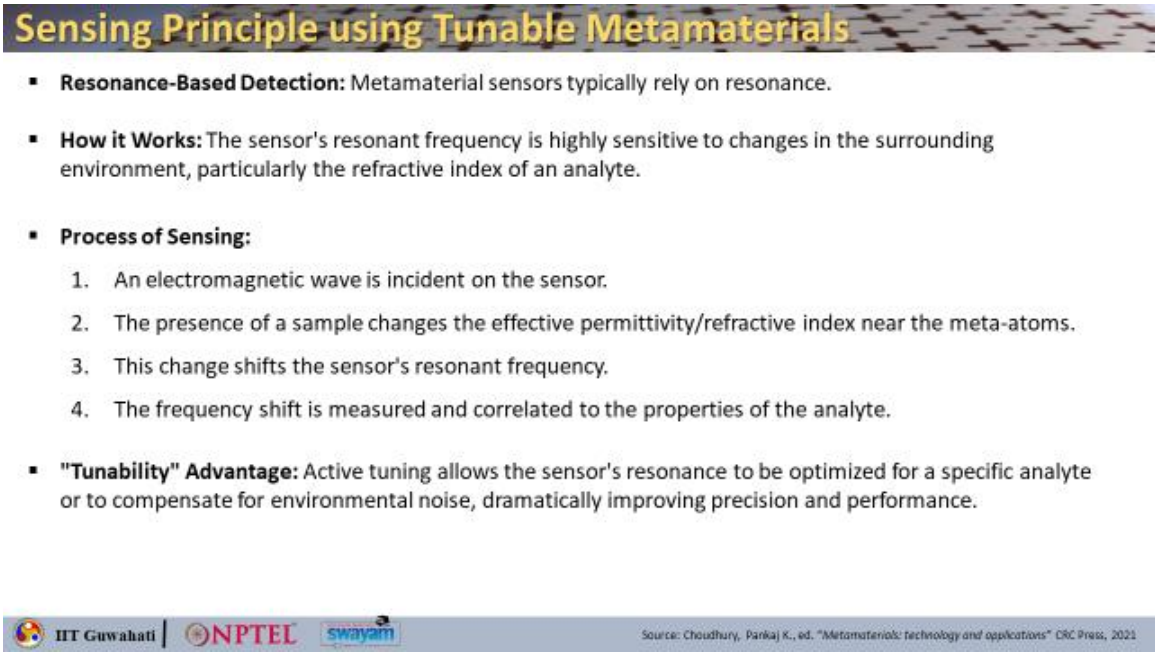
The first one would be refractive index sensing. Here is what happens when there is a change in the refractive index of the analyte that. You are going to sense that the resonance frequency of that metamaterial structure will basically change. And you can detect the change and correlate it back to the change in the refractive index of the analyte. You can also get active tuning with the help of active stimuli like MEMS thermal and liquid crystals that you have seen.

So, that basically giving you dynamic control and that enables rapid reconfiguration for multifunctional sensing.



So, here is a chart that shows metamaterials in biosensing applications. They can be done in the gigahertz domain, which is basically for RF and microwave. You can also do it in the optical frequency domain, which is in the near-infrared to visible frequency range. So, in the gigahertz domain, what is the mechanism? You typically look for splintering or complementary splintering resonator resonance; you look for spoofed plasmon.

Surface plasmon polyatoms, high Q transmission lines, cavity modes, and chiral or polarization-sensitive responses are also what you are looking for. In the case of the optical frequency domain, you look for localized surface plasmon resonance. Fano resonance, hyperbolic dispersion, and chirality. So, in this case, the tuning in the gigahertz domain can be obtained using a varactor diode, liquid metal, or ferrite bias. Whereas in the case of the optical domain, you can use phase change materials like GST or VO2 for refractive index tuning.



So, now let us go into the details of the sensing principle using tunable metamaterials. So, we understood that metamaterial sensors rely on resonance. So, the sensor's resonant frequency is typically highly sensitive to changes in the surrounding environment. Particularly to the refractive index of the analyte.

So, what you can do, the way the sensing works, is that an electromagnetic wave is incident on the sensor. The presence of a sample basically changes the effective permittivity or the effective index near the meta-atoms of the metamaterials. And this change will shift the sensor's resonant frequency. And you can measure the shift in frequency and correlate it to the properties of the analyte. So, that is how match sensing is done.

Now, what is the advantage of tunability? So, active tuning tunability basically allows the sensors' resonance to be optimized for a specific analyte. or to compensate for any kind of environmental noise dramatically improving the precision and the performance of your sensor.

So, if you look into the modeling aspect, the resonant frequency.

Sensing Principle using Tunable Metamaterials

- Resonant Frequency for SRR based Metamaterial calculated using Drude–Lorentz model:
  - The resonant frequency of electromagnetic response (LC circuit), can be expressed using geometric parameters of the SRR:

$$\omega_{LC} = \frac{1}{\sqrt{LC}} = \left(\frac{c_0}{a\sqrt{\epsilon_C}}\right)\sqrt{\frac{g}{w}} \quad \text{.........(1);} \quad c_0 \text{ is velocity of light in vacuum.}$$

here- Capacitance (C): The gap of the SRR acts like a parallel-plate capacitor, where $C = \epsilon_0 \epsilon_C \frac{wd}{g}$ .....(2)

Inductance (L): The ring current creates an inductance similar to a solenoid, where $L = \mu_0 \frac{a^2}{d}$ .....(3)

- Resonance Tuning Mechanism: According to eq. (1), the resonance of the metamaterial, attributed to the **LC mode**, is dependent on its equivalent inductance (L) and capacitance (C).

- From eq. (2) & (3); the resonance frequency is therefore a function of the SRR's size (a), line width (w), gap (g), thickness of the metal (d), and the relative permittivity of the material in the gap (ϵ_C).

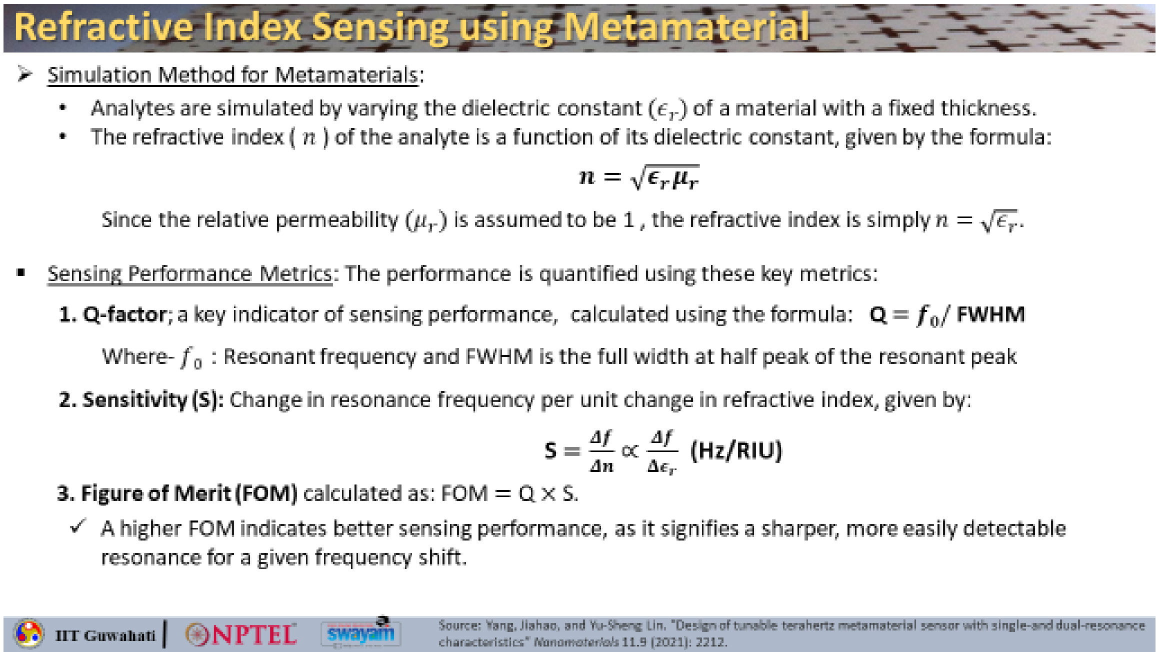
Source: Yang, Jiahao, and Yu-Sheng Lin. "Design of tunable terahertz metamaterial sensor with single-and dual-resonance characteristics" *Nanomaterials* 11.9 (2021): 2212.

The SRR-based metamaterial can be calculated using the Drude-Lorentz model. So, here is the resonance frequency of an electromagnetic response that is modeled as an LC network.

You can take it as $\frac{1}{\sqrt{LC}}$, and then, with the geometric parameters of the split ring resonators, you can correlate them. So, here some examples would be like imagining the split ring resonator, okay? So, there you will have a capacitance that comes from the gap of the split ring, okay. So, that basically acts as a parallel plate capacitor where the capacitance can be taken as $C = \epsilon_0 \epsilon_C \frac{wd}{g}$, w is the width, and g is the gap. You can also get an inductance because there is a ring current that creates an inductance similar to that of a solenoid. And the inductance can be given as: $L = \mu_0 \frac{a^2}{d}$.

So, a is basically the radius and d is the thickness, okay. So, with that, you can see that according to this equation, the resonance frequency of the metamaterial is basically Dependent on the inductance and capacitance of that structure of the meta-atom. And we have also seen that this L and C basically depend on the physical parameter. And the permittivity of the material that you put in the gap, that is epsilon C, okay. So, all these parameters, like SRR size, line width, the gap, and thickness of the metal, All these things are playing a role in deciding the resonance frequency.

So, what are the simulation methods for this kind of metamaterials?



You can conduct the simulation by varying the dielectric constant of a material with a fixed thickness. So, from that, you can obtain what the refractive index of your analyte is. That is a function of the dielectric constant ($\boldsymbol{\epsilon_r}$), given by: $\sqrt{\boldsymbol{\epsilon_r \mu_r}}$. So, really normally for most of the materials relative permeability will be taken as 1. So, n will simply be: $n = \sqrt{\epsilon_r}$.

So, the sensing performance matrix is basically quantized using these key matrices. The first thing is the Q factor, so it is basically a key indicator of the performance of the sensing. So it is calculated as: $Q = f0/$ FWHM , $f0$ is the central frequency or the resonance frequency, divided by the full width at half maximum. So if you normalize your resonance, you can find out the minus 3 dB bandwidth for that, and that will give you the Q-factor. And then you can calculate the sensitivity, which is basically the change in the resonance frequency per unit change in the refractive index.

That can be written as: **S** $= \frac{\Delta f}{\Delta n}$, which is proportional to $\frac{\Delta f}{\Delta \epsilon_r}$. And typically, the unit for sensitivity will be hertz per refractive index unit. The final figure of merit (FOM) will be simply Q multiplied by S. So, when you have a higher figure of merit, it indicates that you have better sensing performance. Because it signifies a sharper and more detectable resonance from a given frequency shift.

So, with that, we move on to discussing the tunable metamaterial-based biosensors, particularly for the gigahertz domain.

Tunable MM-based biosensors in the GHz Domain

So, we will see a tunable high-Q metamaterial-based temperature sensing here.

Tunable High-Q Metamaterial based Temperature Sensing

- High-Q metamaterial units are in demand for precision sensing applications based on liquid metals.
- Most existing high-performance sensors rely on dielectric or magnetic property changes of substrates/superstrates.
- Here is one sensing metamaterial unit based on thermally tunable liquid metals.
- This uses mercury, a liquid metal known for its thermal expansion properties, to construct metamaterial units.
- A basic split-ring resonator (SRR) is designed using mercury as shown in figure.
- The effective equivalent circuit model of this SRR is also shown.

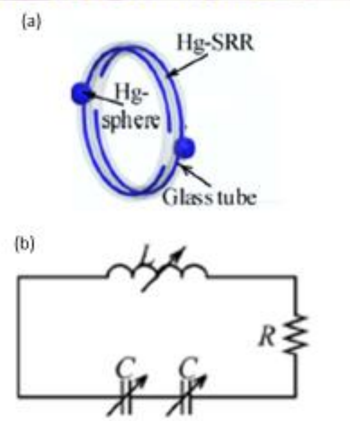


Figure: (a) Systematic representations of the proposed mercury-based SRR, (b) The effectively circuit model of SRR

Source: Ma, Liang, et al. "Thermally tunable high-Q metamaterial and sensing application based on liquid metals." *Optics Express* 29.4 (2021): 6069-6079.

So, these High-Q metamaterial units are in demand for precision sensing applications based on liquid metals. So, you see, you are using mercury here. So, the most exciting high-performance sensors basically rely on dielectric or magnetic property changes of the substrates or superstrates.

So, here is one sensing metamaterial unit based on thermally tunable liquid metal, which is mercury. So, as you can see, this metal mercury is known for its thermal expansion properties and has been used for making this unit cell. Okay, and it is basically in the form of a split-ring resonator. So, you can call this a mercury split ring resonator, and there is a glass tube, okay. So, you can also model these as an effective equivalent circuit models.

So, you have this capacitance modeled here, inductance, and also the resistance. So, this is the effective circuit model for this mercury-based split ring resonator.

Tunable High-Q Metamaterial based Temperature Sensing

- A mercury-inspired split ring resonator (SRR) is introduced to show:
  - Magnetic resonance behavior
  - Negative permeability frequency band shifts under different temperatures.
- A sphere (radii larger than the cylinder) made of mercury is used to amplify the thermal expansion effect for a metamaterial.
  - This is based on the principle that a larger initial volume (V_0) of mercury leads to a more significant volume change (ΔV) for a given temperature change (ΔT).
- Thermal expansion coefficient of mercury:

$$\gamma = (1/V_0)(\Delta V/\Delta T) = 0.18 \times 10^{-3} / {}^\circ C$$

Where- V_0 : initial mercury volume and

$\Delta V/\Delta T$: volume change when temperature varies by ΔT.

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Source: Ma, Liang, et al. "Thermally tunable high-Q metamaterial and sensing application based on liquid metals" *Optics Express* 29.4 (2021): 6069-6079.

Now this mercury based filtering resonator which is introduced last time shows magnetic resonance behavior. It can also show negative permeability and frequency band.

shifts under different temperatures. And the sphere that has a radius larger than the cylinder made of mercury is also used there. To amplify the thermal expansion effect of the metamaterial. So, you can see that this is based on a principle that a larger unit volume, V_0, of mercury will lead to a more significant volume change, ΔV , for a given temperature change, ΔT . So, you can actually write the thermal expansion coefficient of mercury as gamma.

Which is $\gamma = (1/V_0)(\Delta V/\Delta T)$. So, that turns out to be $0.18 \times 10^{-3} / {}^\circ C$, Okay. So, V_0 is basically the initial mercury volume, and $\Delta V/\Delta T$ is basically the volume change.

When the temperature basically varies by ΔT.

Tunable High-Q Metamaterial based Temperature Sensing

- Based on split ring resonator (SRR) design and parameters as shown in figure:
  - Mercury-bar length change inside glass tube as temperature changes:

$$\Delta l = \frac{\gamma\left(\frac{4}{3}\pi\left(\frac{d_3}{2}\right)^3 + \pi\left(\frac{d_1}{2}\right)^2 l_0\right)\Delta T}{\pi\left(\frac{d_1}{2}\right)^2} \quad \text{.........(1)}$$

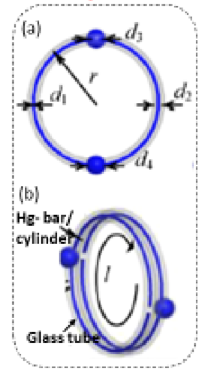
Where: d_3 is the diameter of the larger sphere; d_1 is the diameter of the cylinder. l_0 is the initial length of the mercury in the cylinder and ΔT is change in temperature.

  - Resonant frequency shift due to temperature change (ΔT):

$$\Delta\omega = \sqrt{\frac{1}{(L_{\Delta T} + L_0)(C_{\Delta T} + C_0)}} - \sqrt{\frac{1}{L_0 C_0}} \quad \text{.........(2)}$$

Where: L_0 and C_0 are the initial inductance and capacitance, respectively. $L_{\Delta T}$ and $C_{\Delta T}$ are changes in inductance and capacitance caused by temperature change.

Mercury-based SR



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Source: Ma, Liang, et al. "Thermally tunable high-Q metamaterial and sensing application based on liquid metals" *Optics Express* 29.4 (2021): 6069-6079.

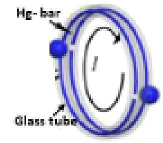
So, based on the split ring resonator design and the parameters, as you can see here, you can calculate the mercury bar length that will change inside the glass tube with temperature can be expressed as Δl , which is basically given by this formula. This is reported by the work published in Optics Express. So, here you see that Δl is basically dependent on this d_3; d_1 is basically the diameter of the cylinder, okay. l_0 is basically the initial length of the mercury in the cylinder, and ΔT is basically the temperature change.

So, if you want to read more about this work, you can go visit this paper. You will have all the information, but I am just showing you how different mechanisms have been applied to make a High-Q sensor. So, here the resonant frequency shift is basically due to the temperature change, which is ΔT. And then you can see that. $\Delta\omega$ is given as: $\Delta\omega = \sqrt{\frac{1}{(L_{\Delta T}+L_0)(C_{\Delta T}+C_0)}} - \sqrt{\frac{1}{L_0 C_0}}$, which is basically the inductance that is changing.

Because of the change in temperature that is now being added to the initial inductance. Similarly, there is a change in the capacitance that is added to the initial capacitance. So, this is the new resonance frequency, this is the old one, and that is basically giving you the change in the resonance frequency, $\Delta\omega$.

Tunable High-Q Metamaterial based Temperature Sensing

- Simulation-based study on a mercury-based SRR metamaterial:
  - Researchers manually varied the mercury bar's length from 21.42 mm to 24.97 mm in a simulation software (HFSS) and observed the changes in its electromagnetic properties.
  - As the mercury bar length increased (corresponding to a temperature increase from 0°C to 57.7°C), the resonant frequency of the metamaterial shifted to a lower frequency.
  - Permeability curves also shift to lower frequency.
  - The resonant frequency shift showed a linear relationship with temperature in the range of 0°C to 30°C.



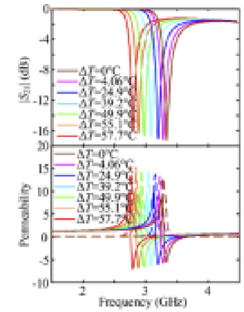


Figure: Simulated transmissions and retrieved permeability curves for SRR

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Source: Ma, Liang, et al. "Thermally tunable high-Q metamaterial and sensing application based on liquid metals" *Optics Express* 29.4 (2021): 6069-6079.

So with that, if you see the simulation results based on this kind of split-ring resonator, okay. You will see that if you vary the mercury bar length from 21.42 millimeters to 24.97 millimeters. In a commercially available simulation software, HFSS, you see how the The transmission and the retrieved permeability curves are changing, which is basically plotted here. So, what you can clearly see is that when you change the length of the bar corresponding to the changing temperature from 0 degrees to 57.7 degrees, the resonance of the metamaterial is basically shifting to a lower frequency, right.

So, from here, this is the hottest one. OK, so you can say from here to here it is going from 0 to 57.7 degrees Celsius. Similarly, the permeability curve also shifts to a lower frequency, and the resonance frequency shifted. Also shows a linear relationship with the temperature in the range of 0 to 30 degrees centigrade. So, that is a good thing; you can use that for sensing purposes.

Tunable High-Q Metamaterial based Temperature Sensing

- Simulation-based study on a mercury-based SRR metamaterial: (see figures)
  - Researchers manually varied the mercury bar's length from 21.42 mm to 24.97 mm in a simulation software (HFSS) and observed the changes in its electromagnetic properties.
  - As the mercury bar length increased (corresponding to a temperature increase from 0°C to 57.7°C), the resonant frequency of the metamaterial shifted to a lower frequency.

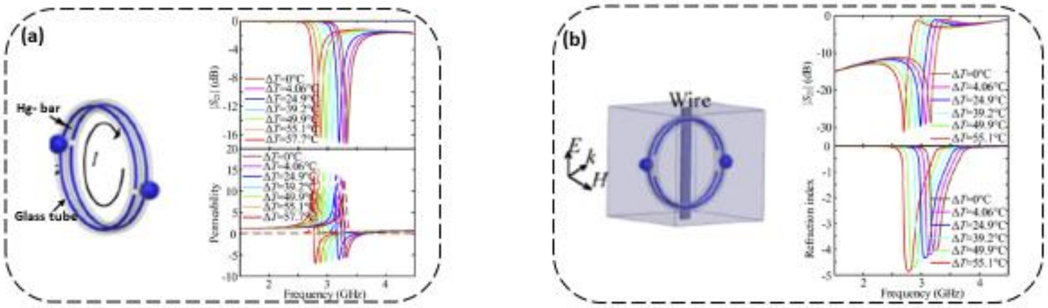


Figure: Simulated transmissions and retrieved permeability & refractive index curves for: (a) SRR and (b) SRR + wire; respectively

So, the simulated transmission, the retrieved permeability, and the refractive index curves are basically shown. Here it is for the SRR, and here it is basically for the splitting resonator and a wire-like structure.

So, here again, similarly, the mercury bar length was changed, and it was plotted. So, similarly, we also see that in this case, the resonance frequency is basically shifting to a lower frequency.

Tunable High-Q Metamaterial based Temperature Sensing

- Simulation-based study on a mercury-based SRR metamaterial: (see figures)
  - Permeability and refractive index curves also shift to lower frequency with temperature increases.
  - The resonant frequency shift showed a linear relationship with temperature in the range of 0°C to 30°C.
  - Sensing Performance:
    - **Linear tuning Scale Factor (S):** The tuning ability was measured to be **7.2 MHz/°C**.
    - **Sensitivity:** Temperature sensing sensitivity calculated to be approximately **1.4×10^{-7} °C/Hz.**
    - Q-factor, and FOM for mercury-based SRR under different mercury bar lengths (correspondingly the temperature changing amounts) are also shown in fig.
  - Sensitivity can be enhanced with larger mercury sphere and thinner mercury bar (per Eq. 1).

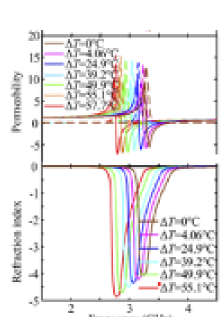


Figure: Simulated retrieved permeability & refractive index curves for proposed SRR MM

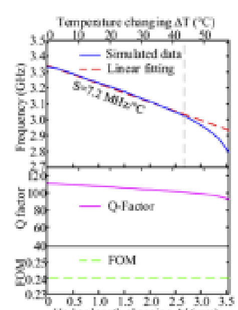


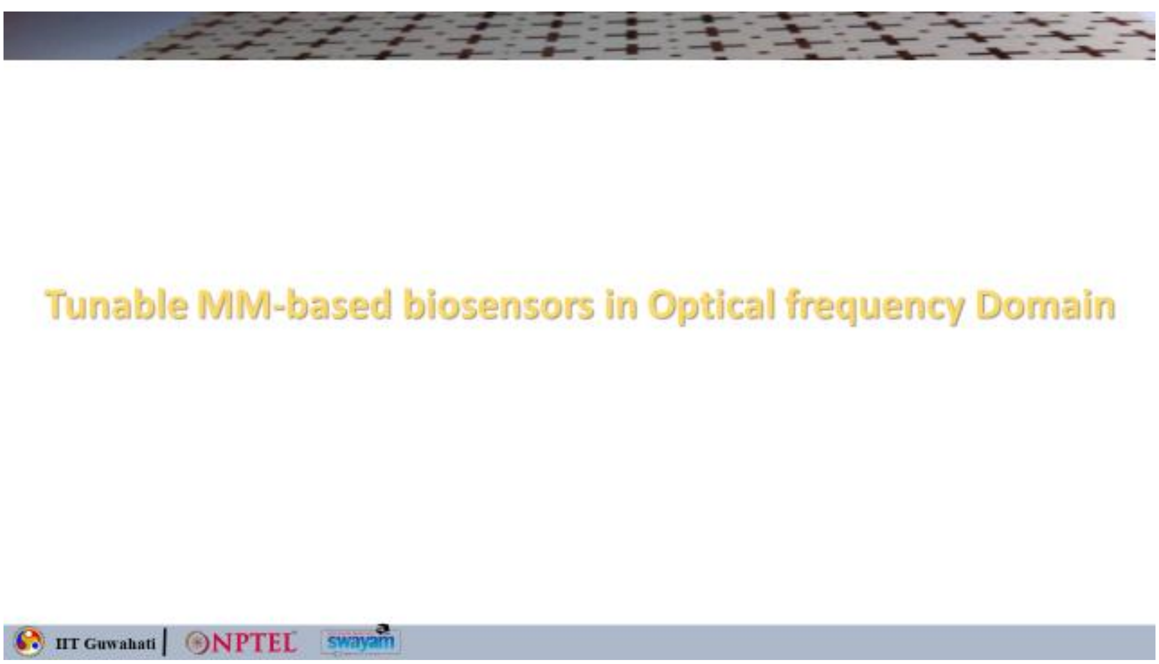
Figure: Resonant frequency shift, Q-factor, and FOM of mercury-based SRR under different mercury bar lengths

Further analysis also shows that the permeability and the refractive index curve shift to lower frequencies with the increase in temperature. So, finally, what is important is that if you see the resonance frequency shift with temperature, as We mentioned that over 0 to 30 degrees, it is basically showing a linear fit, which is very good.

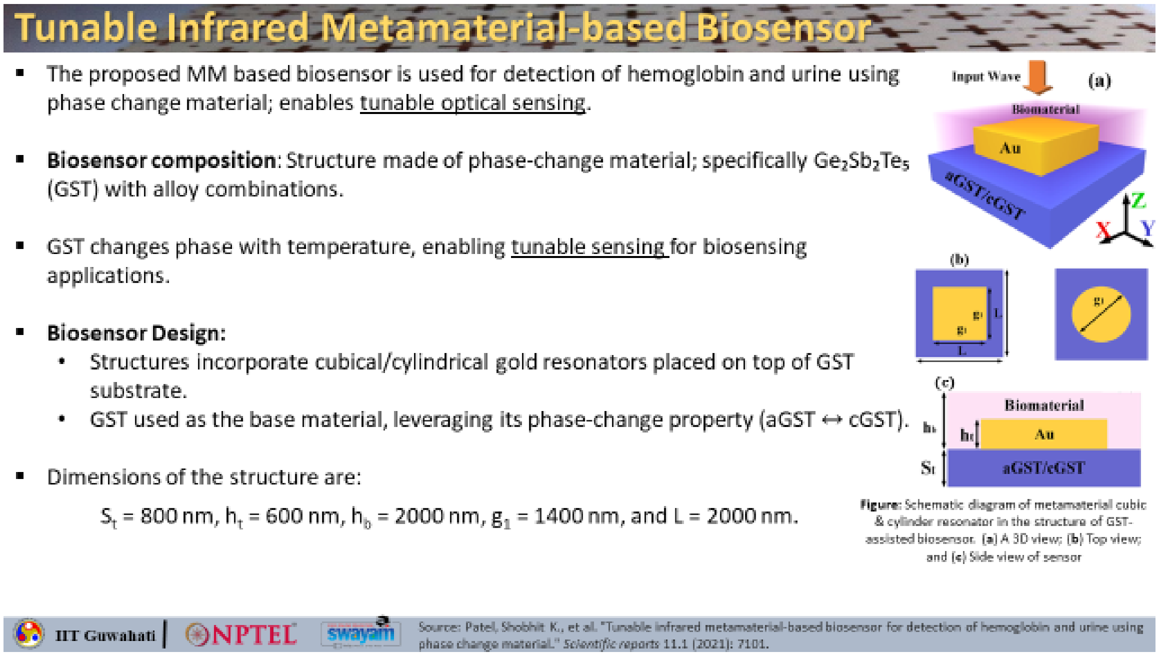
And this is basically the sensitivity of 7.2 megahertz per degree centigrade, which is the linear tuning scale factor that was obtained for this sensor. And the sensitivity was obtained to be 1.4 into 10 to the power of minus 7 degrees Celsius per hertz. So, the Q factor and the figure of merit of this mercury-based plectrin resonator under different mercury bar lengths. Which basically corresponds to the temperature change amounts; they are also shown in this figure.

So, what we understood is that you know the sensitivity can be further enhanced with a larger mercury sphere. and a thinner mercury bar because that is in the equation 1. So, the physical relation actually shows you that. So, the length, ok, is here and d 1 is the diameter ok. So, with that, you can basically change the temperature; you can have more change in the mercury bar length.

One is in the numerator; this is in the denominator, which is the diameter of the cylinder.



So, with that, we move on to the next topic, which is how we can design a tunable metamaterial-based biosensor in the optical frequency domain.



So, here is the schematic of a metamaterial cubic and cylindrical resonator. So, there is a structure; there is a gold-based structure on the GST-associated structure, or it is basically a substrate for GST. And you will see this part is basically the biomaterial that you are sensing, and your wave will be falling from the top.

So, this kind of proposed metamaterial based biosensor, this work was reported in scientific reports by this set of authors. So, they have basically used this kind of thing for the detection of hemoglobin in urine using phase change material that enables tunable optical sensing. And here, the biosensor composition, as I already discussed, is made of a phase change material. Which is basically GST with some alloy combinations.

Why GST? Because GST changes phase with temperature. So, it enables tunable sensing for biosensing application. So, you can see the design here that the structure basically incorporates a cuboidal or a cylindrical gold resonator That is placed on this GST substrate, and GST here is used as a base material. So, it can basically change its phase with temperature from amorphous to crystalline. So, a is for amorphous, c is for crystalline, and these are the dimensions of the structure. So, the surface thickness is 800 nanometers, the height of the gold structure is 600 nanometers, and the biomaterial one is about 2 microns or 2000 nanometers.

And then these structural dimensions g1 and L are basically 1400 and 2000 nanometers. So, what they have done is they basically made biosensors that include three different unit cells. Something like UC 1, UC 2, and UC 3; these are basically three different unit cells. Similarly, for the cylindrical one as well, these are the dimensions of each of these unit cells. So, overall, you can see the size and g1, which is basically the inner structure that is also changing.

Tunable Infrared Metamaterial-based Biosensor

- **Unit Cell Configurations:**
  - Biosensor includes three different unit cell designs (UC1, UC2, UC3).
    - **UC1:** $L \times L = 2000 \times 2000$ nm^2 with $g1 = 1400$ nm
    - **UC2:** $L \times L = 666 \times 666$ nm^2 with $g1 = 466$ nm
    - **UC3:** $L \times L = 400 \times 400$ nm^2 with $g1 = 280$ nm
  - Each has a different size, which affects the sensor's tunability.

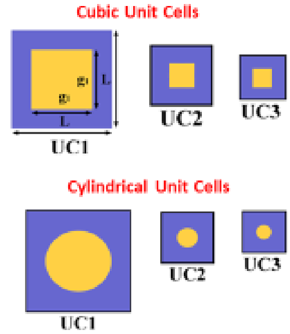


Figure: Top view of metamaterial's UC

- **Operational Principles:**
  - Sensing Mechanism: The sensor detects changes in the refractive index of an analyte (e.g., hemoglobin or urine) by measuring the shift in its absorption peaks.
  - Tunability: Phase transition of GST (from amorphous to crystalline) allows spectral response to be tuned.
    - ✓ Also; the number of resonators in an array provides tunability for both aGST and cGST-based biosensors.

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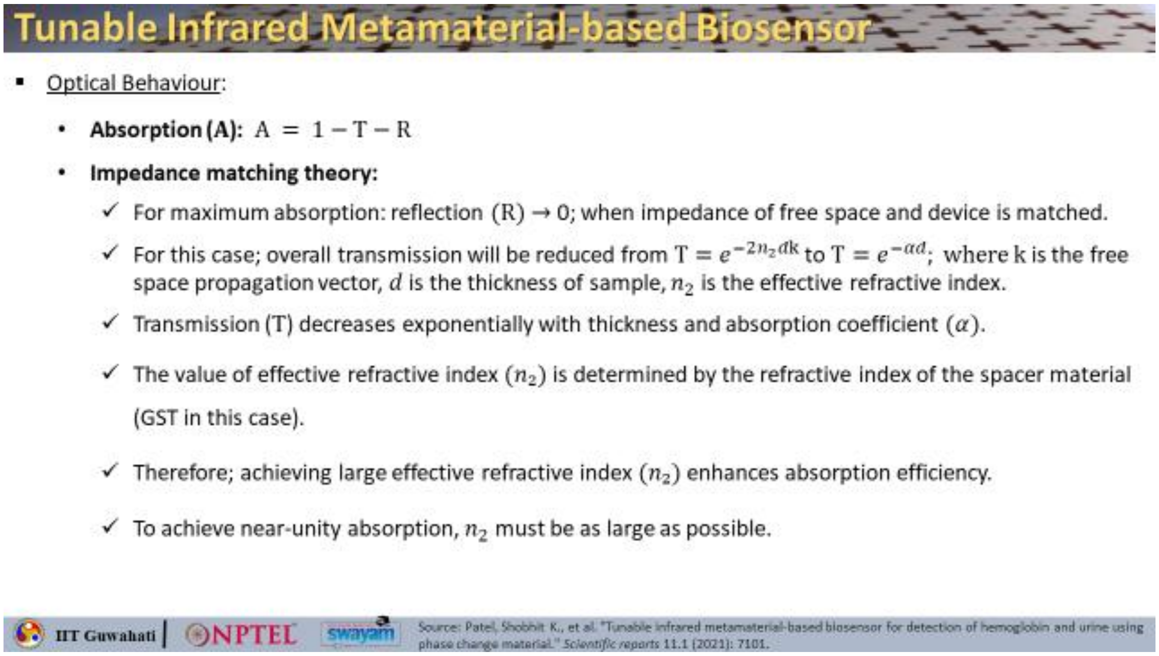
Source: Patel, Shobhit K., et al. "Tunable infrared metamaterial-based biosensor for detection of hemoglobin and urine using phase change material." *Scientific reports* 11.1 (2021): 7101.

Now, why they have tried three different ones is because each has a different size and that will affect the sensor's tunability. Now, to quickly remind you of what the operating principle is here. So, I will need to understand the sensing mechanism. So, here the sensor basically detects changes in the refractive index of an analyte. That can be hemoglobin or urine by measuring the shift in their absorption peaks.

Now, tunability comes from the phase transition of GST that occurs with temperature. When it moves from amorphous to crystalline, that basically allows the spectral response to be tuned. Also, the number of resonators in the array provides tunability for most for both amorphous and crystalline GST based biosensors.



Now, we can observe the response in optical behavior. So, if you want to measure the absorbance, that is basically A, which is $1 - T - R$; T is the transmittance and R is the reflectance.

So, what is not transmitted and reflected is basically absorbed. You can also discuss this from the impedance matching theory that for maximum absorption, what you want is to have no reflection, right? So, when the impedance of the free space and the device is matched, there is no impedance mismatch; there is no reflection. And for this case, overall transmission can be reduced from $T = e^{-2n_2 dk}$ to $T = e^{-\alpha d}$. So here, k is basically the free space propagation vector, and d is the thickness of the sample. Or the thickness of the sample, and n_2 is the effective refractive index.

So you can see all these details in this paper as well. I am telling you that the final goal here is to demonstrate how the sensing performance looks with metamaterials. So, we will see that the transmission basically decreases exponentially with thickness and the absorption coefficient alpha. And the value of the effective refractive index n_2 is basically determined by the refractive index of the spacer material, which is GST here. So, when you change the GST phase from amorphous to crystalline, there is a change in the refractive index. So, if you achieve a large effective refractive index n_2, that will basically enhance the absorption efficiency.

And to achieve a near unity absorption, your n_2 should be as large as possible.

Tunable Infrared Metamaterial-based Biosensor

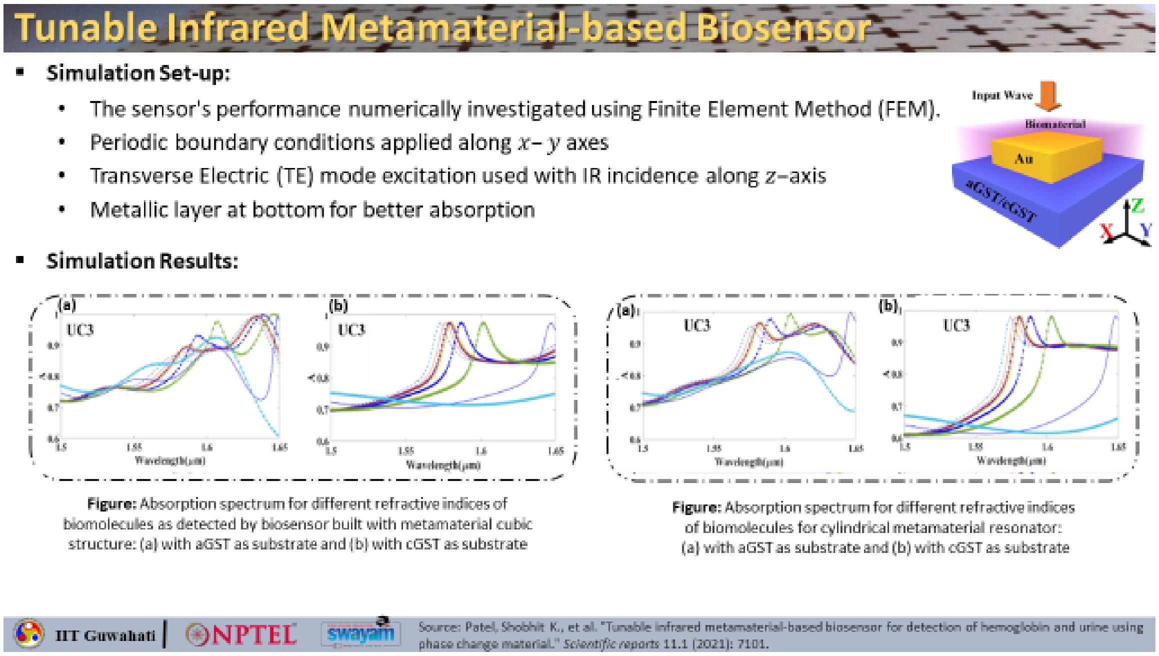
- **Sensor testing**:
  - Built using amorphous GST (aGST) and crystalline GST (cGST) in different structural designs.
  - Tested with varying biomolecule concentrations:
    - **Hemoglobin**: 10 g/L, 20 g/L, 30 g/L, 40 g/L.
    - **Urine**: 0–1.5 mg/dL, 2.5 mg/dL, 5 mg/dL, 10 mg/dL.
  - The refractive index of hemoglobin and urine in different concentrations is shown in Table:

Biomaterial-Sample	Hemoglobin sample concentration (g/l)				Urine sample concentration (mg /dL)			
Concentration	10	20	30	40	0-1.5	2.5	5	10
Refractive Index	1.3412	1.3607	1.3995	1.4383	1.336	1.339	1.342	1.348

Source: Patel, Shobhit K., et al. "Tunable infrared metamaterial-based biosensor for detection of hemoglobin and urine using phase change material." *Scientific reports* 11.1 (2021): 7101.

So, with that, we will go for the sensor performance testing. So, the sensor is built with amorphous GST (aGST) or crystalline GST, okay. So, we will have different structural designs. So, when you do the testing with varying biomolecule concentrations, say Let us consider hemoglobin: four different concentrations and urine of four different concentrations.

This is how the refractive index of the hemoglobin and urine in the different concentration look like. So, you see there is a steady increase in the refractive index with concentration. Similarly, you can see that here. So, that will basically mean that if the refractive index of this material changes, it will alter the optical performance, and that is how the sensing is done.



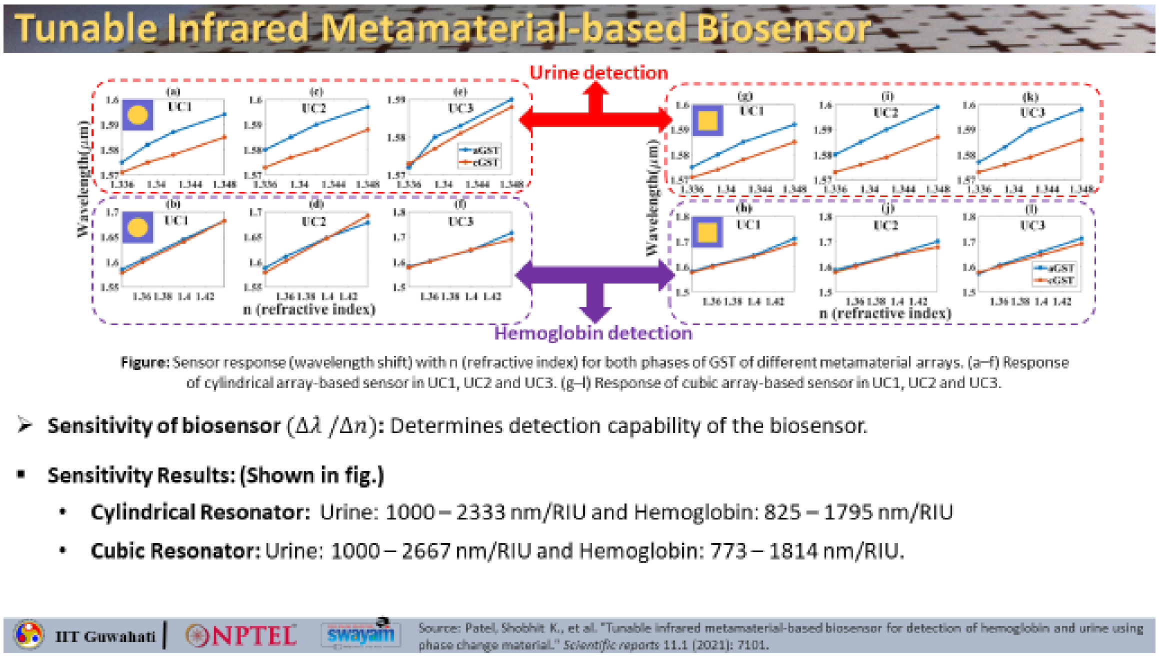
So, this was reported through simulation the senses performance was numerically invested investigated using FEM method.

So, they put periodic boundary conditions along the x and y directions. So, it is kind of a very large sensor they made because they have put periodic conditions in place. And then they have put T transverse electric mode excitation for the IR incidence along the Z direction. They are also considered a metallic layer at the bottom to completely kill the transmission so that absorption increases. So, here are the simulation results for different unit cells. So, it shows the absorption spectrum okay for different concentrations of molecules.

So, this has a GST and this has c GST as the substrate. So, you can see they behave differently because they also have different properties, right? Similarly, for different unit cells, you also see a similar kind of observation. For the left one, it is with aGST as substrate; the right one is with cGST as substrate, okay? So, this is for unit cell 3, the one where we have described a similar kind of observation. So, what you see here is that finally, when you plot the refractive index against the wavelength. So, this is how you know the absorption or the spectral response is basically shifting; that means, the absorption peak basically keeps shifting with the change in refractive index. So, you can see that for the two cases, the blue one is for the amorphous, and the other one is for the crystalline cGST.

So, you see that in this case, they are almost equal, the shifts, but it is very different when you are in this particular range, okay. So, this is 1.57 to 1.6, and this is the range of the refractive index that is being changed.

A similar observation is also here. So, they all tell you about the urine based sensing this one and this is for the hemoglobin-based sensing. So, another difference is that here you are using cylindrical structures for sensing, and here you are using square unit cell structures for sensing. So, the top row is basically for urine detection, and the bottom row is for hemoglobin detection.



So, what do you see here is that the sensitivity of the biosensor basically determines the detection capability of the sensor and if you calculate the cylindrical resonators for urine, it reports 1000 to 2333 nanometers per refractive index unit.

Whereas the sensitivity in the case of hemoglobin is lower, it ranges from 825 to 1795 nanometers per refractive index unit. And for the cubic ones, this is basically the comparison between the cylindrical one for urine and the cylindrical one for hemoglobin. If you arrive at the right figure. So, the cubic resonator for urine gives even better sensitivity. It is also giving much higher, not much higher, but a little bit higher for the hemoglobin as well.

So, a quick comparison tells you that you know the. Cubic ones, the cubic resonators have better sensitivity compared to the cylindrical ones.

So, with that, we conclude this lecture, and if you have any queries regarding this lecture, you can drop an email to this email address. Thank you.