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Optical Fiber Sensors
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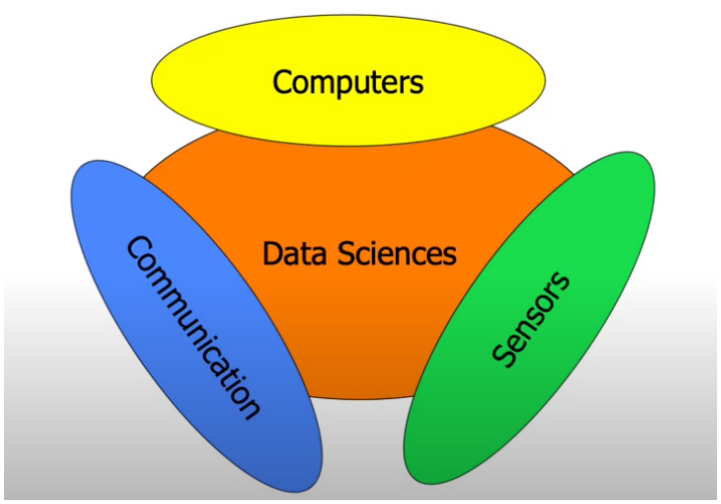
Lecture No. 01
Introduction to Optical Sensors

Hello, and welcome to this course on optical sensors. My name is Balaji Srinivasan; I am a faculty at the Department of Electrical Engineering, IIT Madras. As we begin this course, you must have a lot of questions why, what, how and so on. So, why optical sensors, what are these about, how do you make optical sensors and all that. And these are the kind of things that we will discuss as far as this course is concerned.

So, before I go on to talking about details about optical sensors before we really get into our course, let me first try to give you a flavor for what you are going to see in this course through a presentation that I have for you. So, let me just get into the presentation, and we will see if we can answer some of the questions.

So, we live in a world of cyber physical systems. So, you want to ask the question, what are cyber physical systems? Well, cyber physical systems are a triad of computers, communication, and sensors. So, this actually defines a lot of things that we see that's happening around us, and we will see a few examples. But this triad, backed up by, powered by data sciences, is actually what is driving a lot of technologies that are happening around us. And this, essentially, is providing us all the information that is necessary to make smart decisions in a lot of systems that we see around us.



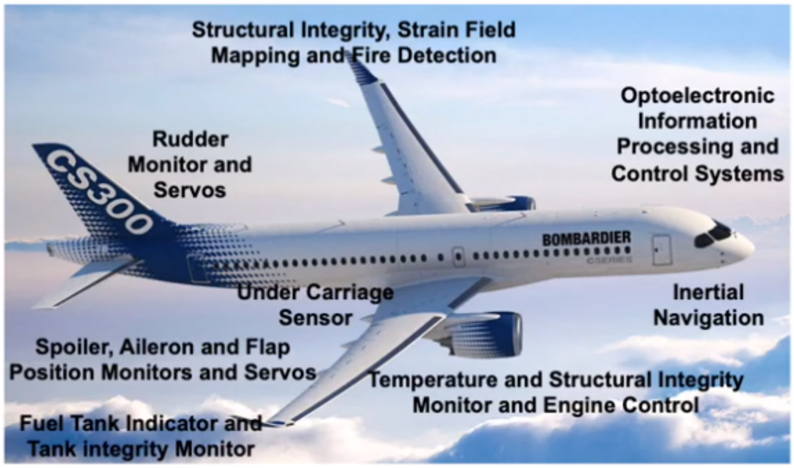
One such example is the smart grid. So, what we see in a smart grid is there are these power generating stations, maybe we burn coal, we have hydroelectric power, wind power, and so on, wave energy, and solar power, and so on. So, we have all these generators, and those are actually plugged into the grid. And then you have all these consumptions that are happening in big industries, in big cities, urban areas, as well as, your residential areas in all these places, you consume electricity, so you need to have a distribution network. And you need to have sensors all across the distribution network, which are monitoring how power is generated, how power is consumed on a real time basis.

Courtesy: https://www.sdelcc.com/fields/energy/smart-grid/

To do that, then the sensors need to communicate all the relevant information to a central node, wherewith the help of processes and with data sciences, you are able to make some smart decisions about this, this entire system. So, this smart grid is one such example of a cyber physical system.

Let us go ahead and see another example of a cyber physical system. And for this, I would like to post this picture of an airplane. So, what is happening in an airplane? Now, for this airplane to work properly, you need to have a lot of these systems within the airplane that you need to work on a synchronous basis. And to do that, once again, you are going to need several sensors. You will need communications across from those sensors to the central node. Then you need computers to process that information and give this information to the pilot or copilot to make decisions on a real-time basis.

- Distributed strain sensing
  - Bridges, dams, aeroplanes, ships etc
  - Structural health monitoring
  - Perimeter sensing
  - Timely intervention can save lots of $$$



http://www.bombardier.com/en/aerospace/commercial-aircraft.html

Center for Intelligent Optical Networks
IITM Proprietary Information

So, one such example that is already present is the inertial navigation sensor. For example, in a fiber optic gyroscopes are widely used for inertial navigation. Then, of course, you have optical fibers that are carrying information from one part of the airplane to the other part, and that is helping the information processing and the control systems. So, that is already available in a lot of airplanes today.

But there are a lot of other opportunities, and this is where this course becomes important because you could potentially have sensors that are, that could be monitoring the structural integrity of different parts of the airplane or the engine. You could have things like the fuel tank indicator, and so on. So, there could be a lot more and more sensors that could be deployed. And this is actually the real problem.

And when you look at cyber physical systems, and I go back and flash this picture again, you see these computers have been around with this for several decades, now to the point that we take them for granted and a lot of applications. Thanks to a lot of developments in the last two decades, communications is also becoming a fairly mature field, fairly reliable field. But from this perspective, when you look at sensors, there are not as many sensors as we would like.

And, the smart grid is one example where we would possibly like to see sensors deployed all along the distribution lines, so that you can clearly make out where are the major losses that are happening in the distribution. And also, if there are any faults that are happening along that network, you could get real time information about those faults.

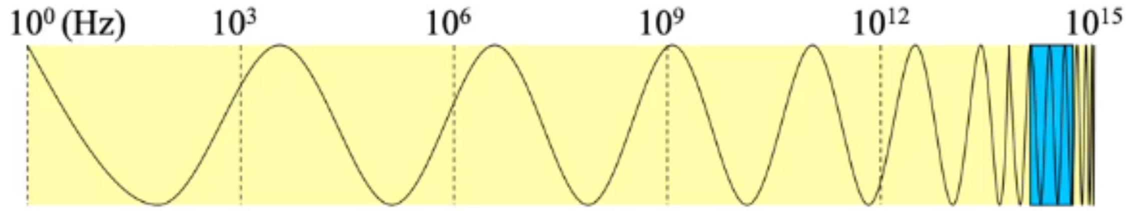
So, we could use a few more sensors in these cases. And so is the case that we are talking about here. As far as an airplane is concerned, you could deploy several more sensors across the airplane, and that can give us real time information. And what we gain from all this information in this is actually an example of distributed, what is called distributed strain sensing.

And what we gain from this sort of information is that you could, by monitoring this structural health of whichever capital intensive structure that you are looking at, it could be an airplane, or it could be a bridge or a dam or a ship or any capital intensive structure that you can think of, if you could get real-time information about that structure. These faults are developing in the structure, and if you have an early warning about these faults, you could potentially try to go back and address those faults before they become much critical fault that could lead to some permanent damage and so on.

So, in essentially, what we are talking about is we could save a lot of money, or we could protect the investment that we have made in these structures by doing condition monitoring of the structure or structural health monitoring, if you may, and that could be a reasonable way forward. And a key to achieving that, what I am trying to motivate you to understand is development of appropriate sensors. And that is actually one of the key goals as far as this course is concerned.

Yet another application that I could talk about is perimeter sensing. A country like India has a border with several other countries where we need to secure our borders, we need to monitor our borders, we need to look at possible intrusions across the border. And what if we could deploy a sensor that could do these intrusion detections in real time and could warn people appropriately so that appropriate action could be taken.

So, this once again, is a case where timely intervention can save a lot of money, so that is sort of the background, so let us just go into and specifically see why you may need an optical sensor for several of these applications, that is what this course is about.



- Optical sensing
  - Sub-wavelength precision (sub-μm)
  - Optical density of materials sensitive to strain/temperature/pressure
  - Non-invasive and non-destructive
  - Mature technology; easy availability of components

Of course, when you talk about optical sensors, you are referring to sensors that are working with at optical frequencies. And here you see the electromagnetic spectrum. So, you are starting from hertz, kilohertz, megahertz, gigahertz; this is where most of your communication is getting done. Your mobile communication, for example, is happening over here, wireless communications happening over here. But of course, you go up to 10 power 14 hertz, this corresponds to optical frequencies and that is clearly where optical communications are happening.

Now, these optical frequencies are quite important from a sensing perspective also, because of the fact that these optical frequencies correspond to wavelengths which are in the order of micrometers. And that sort of wavelength allows you to achieve sub wavelength precision or sub-micron precision, in this case, with a lot of your optical sensors. And this is one of the things that we are going to actually look at in little more detail as far as this course is concerned, you will find that there are several applications where we can achieve very high level of precision with measurement, because of the use of optical frequencies.

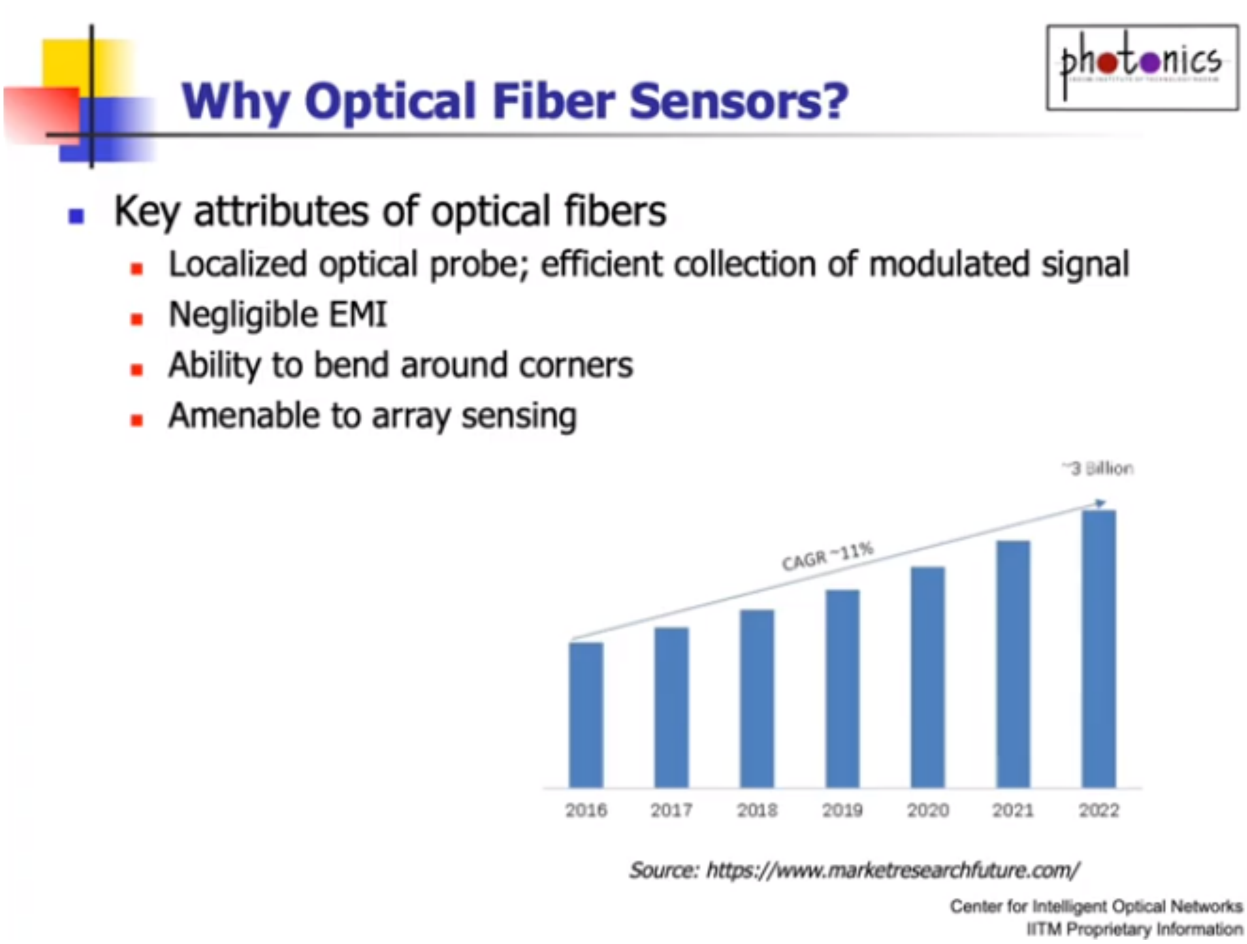
It also is important to note that the optical density of materials is sensitive to physical parameters such as strain, temperature, pressure, and so on. And, and that is actually a very good opportunity, because, what that tells you is, if you have these physical parameters that are changing, that can change the optical density of the material. And so, if you are sending an optical wave through this material, you can pick up those changes and you can possibly get an idea of what are these physical parameters that are getting changed.

And, and one of the important things that you look for as far as sensor is concerned, it should be non-invasive, it should not compromise the regular function of whichever system that you are deploying the sensor into. So, we will find that optical sensing is actually working out very well from that perspective, and it should be non-destructive, meaning the sensor by itself, by while deploying the sensor itself should not compromise the strength of a structure.

For example, while putting in a sensor, you should not have a crack that is developing in the system. So, it completely defeats the purpose if it is, you know if it ends up causing damage to the structure, so it must be a non-destructive mechanism solution that is deployed for these applications. But it also helps that when you talk about optical sensors, we are relying on a fairly mature technology and that for that, we need to thank optical communications because, how optical communications as come in the last couple of decades and completely revolutionized the field of communications.

And it means that the components that you need for a typical optical fiber sensor is relatively easy. And as far as this course is concerned, for the most part, we are going to be dealing with optical fiber sensors.

So, let me spend a little bit of time to say, what is an optical fiber sensor, why do we need an optical fiber sensor? Well, that why the question is relatively easily understood. If you understand why optical fiber communication makes a lot of sense. We know that optical fiber communication makes a lot of sense because the optical fiber, which consists of a core surrounded by relatively lower index, cladding region is intrinsically very low loss and the loss could be down to 0.2 dB per kilometer, if you consider a wavelength of 1550 which is where most of the communication is happening.



And what that means is you can send light over long distances, and that is a fairly good aspect as far as optical fiber sensors also concerned, which means that you can actually send a probe, in this case, an optical probe, which can be confined along with the core of the optical fiber and light could be sent to fairly long distances. Whatever information you want to gather, it could potentially be gathered, once again collected in the core of the optical fiber and then brought back, so you could essentially probe over fairly long distances.

And this is actually a key aspect because we will see there are these class of sensors called distributed fiber sensors, and they do the job of sensing information over literally 10s of kilometers of fiber. Let us say the fiber is deployed along the oil or gas pipeline, that is going over several 10s of kilometers. So, it can pick up information with 1 meter spatial resolution all along the length of the fiber and provide you that information at the terminal equipment.

So, typically, we are talking about, let us say 10 kilometer distance, you have 1 meter spatial resolution, you are talking about 10,000 sensors that are concatenated in a single optical fiber. So, that is that could be the power of this technology, the optical fiber sensor technology and that is made possible because of the fact that this optical fiber is relatively low loss. So, it can send information over long distances, you can gather information from remote places as well.

Another thing that helps very, very important aspect that helps optical fiber sensors is that it has negligible EMI. What is EMI? EMI is Electromagnetic Interference. When you consider an electrical sensor, you are going to have these wires that are connecting these electrical sensors. And whenever you have these wires, there is always a possibility of some external electromagnetic radiation coupling into those wires, which is what we call as electromagnetic interference. And this can potentially give you false information as far as a sensor is concerned.

So, if you have negligible electromagnetic interference, for example, we talked about this airplane where you need to have very high density of sensors. And in those cases, all these electrical sensors, if you deploy them, there could be a huge problem in terms of electromagnetic interference between different sensors and from external sources of electromagnetic radiation. Whereas, if you do it in an optical fiber, you can circumvent some of these problems.

And, and another aspect of optical fibers that gives a very good advantage is its ability to bend around corners, we know that the optical fiber today is coming into our campuses into our offices into our homes. And when it is coming into such buildings, we see that the fiber has to be bent around the corner and all of that and we have, specific fibers that provide very low loss when you are bending these fibers. So, you can take care of this bending losses by using these specially designed fibers.

But in short, it has an ability to bend around corners and that is actually a very good advantage when you are talking about routing these fiber sensors around narrow spaces. And we already talked about it, it is amenable to array sensing you can send light over long distances and you can essentially get information that you would otherwise get with array of single point sensors. And this distributed fiber sensing like I said is really a game changer as far as sensing is concerned specifically using optical fibers.

And the graph here, it is coming from the source is showing the because of all these reasons the optical fiber sensor market is actually growing quite rapidly, we are looking at billions of dollars a market already and, having a healthy growth trend. But in all of these, applications, you have one key aspect, which is cost to assess performance. And as an engineer or a scientist, this is actually a very, very important aspect to understand.

Let me take the example of a mobile phone. Today, most of us have smartphones and when you consider a smartphone, you can go into high end phone like iPhone, and which gives you excellent performance. But what do most of us use most, I mean, several of us at least, do not have iPhones, we prefer something that is, that does as good a job or maybe not as good performance, but certainly does not pinch our pocket.

So, we have a lot of android based phones that are on the market, which are also smartphones, which does a fairly good job of providing us communication capability along with your cameras, your networking and all that right. So, it gives us all that option at a fraction of a cost compared to the top of the line iPhone. So, what are we talking about, we are talking about this tradeoff between cost versus performance.

It is not critical in several applications that we have the highest performing sensor out there, you may need only a certain level of performance of the sensor, but you need to do this at a much lower cost than what this high performing sensor can provide okay. As an engineer, you will be able you will be facing situations where you will have to play this sort of a trade off in very careful manner.

So, you need to understand your market, your customer, what is their request, what is the performance that they require, and what are they willing to pay for that. And your job is to not just pick whatever, you know, with the highest performing sensor out there to fit this application with whatever costs, you have to fit within the budget. So, that means you need to be judicious about picking the sensor that you want and several cases maybe you have to develop your own sensor for that particular application.

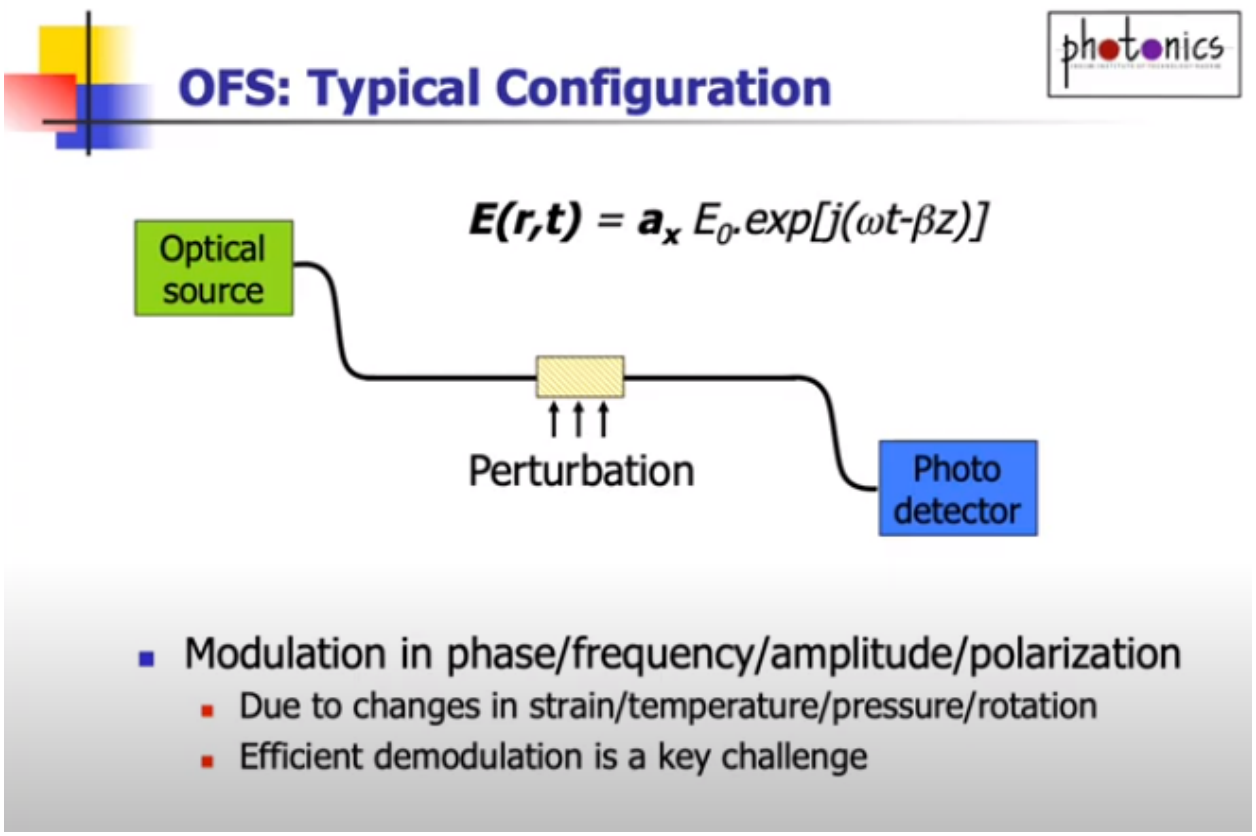
This course is all about that it is actually allowing you to understand what are the fundamental principles as far as optical fiber sensors are concerned. And it allows you to fine tune the performance so that it actually meets the cost requirement of your customer, so that is what we are going to try to teach. Now, before we go forward, let us actually try to understand what an optical fiber sensor is all about.

So, optical fiber sensors OFS, in short, a typical configuration would be something like this, you have an optical source, which could be a laser, it could be a light emitting diode or whatever. And in this case, we are talking about an optical fiber sensor. So, we are talking about that light source connected to an optical fiber. And when we look at light traveling down this fiber, we are talking about an electromagnetic wave that is propagating down this fiber.

And if you look at the electric field component of that electromagnetic wave, that electric field component is going to be defined by several parameters. The popular one is the amplitude of the electric field. And this actually defines the intensity of the light that is propagating down the fiber that is the most apparent but it also has polarization associated with it, here I am saying that this is actually an electric field that is polarized along the x direction and the propagation is along the z direction, along the length of the fiber.

And then it also has a frequency associated with that. So, we are talking about the phase term where the phase term is primarily constituting of two terms. One is the evolution with respect to time, which is governed by the frequency of the light, that is propagating to the fiber. So, that is another characteristic. And then you have a certain phase that you accumulate during propagation through this phase constant, beta. So, the beta times z corresponds to the propagation phase that is accumulated.

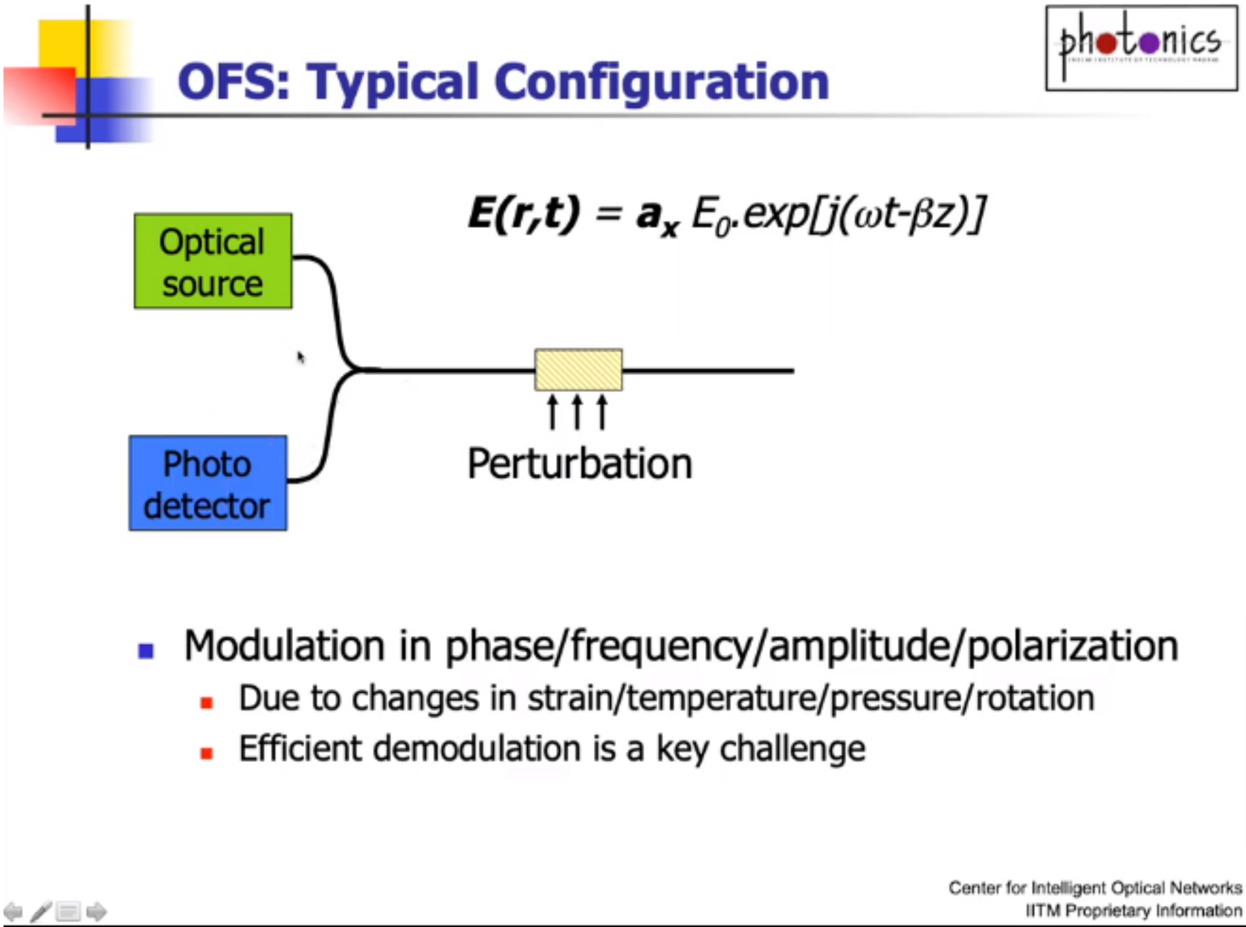
So, we have these typical properties of an electromagnetic wave, characteristic of electromagnetic wave in terms of amplitude, in terms of polarization in terms of frequency, and in terms of phase. All these actually provide us opportunities to, make a sensor. How? Because when you introduce a perturbation to this optical fiber, that perturbation typically changes all these parameters okay. So, you have an opportunity to learn about this perturbation by observing what is happening with all these quantities Okay.



Now, how do you do that observation? Well, of course, you would want to put an optical receiver which consists of a photo detector at the other end of the fiber, and then you can capture the light that is coming through. There is a problem here, though, the problem typically is the photo detector here, the optical receiver here, not only captures the light that is modulated due to this perturbation, but it also captures a lot of unmodulated light. So, what am I talking about?

You are actually seeing me on your screen, and that is because I have a light source that is falling on me. And my, the light is actually scattered off, and it is captured by the camera over here, in front of me, both the light source as well as the camera are in front of me. Suppose you are sitting behind me, and I am making a gesture like this. What will you see? Well, you will see a part of what the light that is modulated by my gesture, but major part of the light that you see is going to come directly at you from the source. And, this might end up blinding you to the point that you may not be able to make out the gesture that I am making.

Now, contrast this to this situation, where you put your optical receiver on the same side as your source. So essentially, you are looking at light that is backscattered from this perturbation, and that is typically the situation that we are having right now. So, you have the light that is falling on me. And I am the perturbation, and the scattered light from me is reaching you through this camera, which is which is essentially your optical receiver. So, what are the advantages of that?



Well, the key advantage is that my background is relatively dark. So, I am, you are able to make out my gestures with much higher sensitivity than you would otherwise do, if you are in our detector for your receiver was in this direction. So, this is actually a very, very important aspect to understand, by looking at the backscattered configuration, you could potentially make highly sensitive detection of information and the information that we are trying to gather here is essentially the perturbation of the fields or the other optical wave that is propagating down the fiber.

The perturbation is changing all these characteristics like phase, frequency, amplitude and polarization. So, it results in the modulation of that. And this could be due to the perturbation which could constitute strain, temperature, pressure, rotation, all these physical parameters. But in all of this, a key part to understand is that we are dealing with an inverse problem. What do they mean by inverse problem? Well, I am seeing, say some change in the intensity of the light, and I am trying to make a decision based on that. So, I need to attribute that change to this perturbation. It could have been caused by this perturbation, or could be caused by something else, you don't know.

But, typically, you are trying to make an observation and then say, based on that observation what could be the perturbation that caused it? So, that is what I mean by a inverse problem. And that is actually a fairly tricky thing to do, because, for example, that perturbation could result in an intensity change here, and there could be some other perturbation as the light is propagating back towards the photo detector which can also cause some changes in the intensity, then can cause some noise, essentially, in your detection. And, so that is something that you want to be looking at.

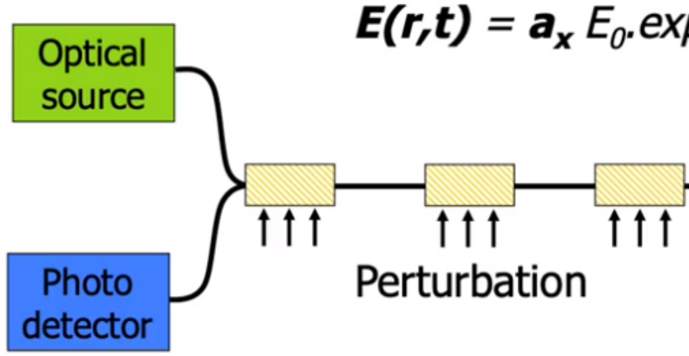
And but the perturbation can also because of multiple terms, like strain, temperature, pressure, rotation. So, suppose both strain and temperature are changing, let us say the face of the light that I am getting over here, you do not know, what caused it. So, you are just seeing a change in face as a function of time, but you do not know whether it is caused by strain or temperature. And that is actually the classic issue as far as inverse problems are concerned.

And you need to be coming up with a solution where you can unambiguously pick up this attribute this changes to changes in strain or temperature, and that is part of the engineering that you are going to have to do and we will look at some of those techniques as far as this course is concerned.

But we are at a point where we can possibly understand what is happening as far as this course is concerned. So, you could have sensors that work primarily on detection of changes in amplitude, we could have sensors that look at changes in phase. So, we call it phase modulated sensors, you could have frequency modulators sensor or could have polarization modulators sensor.

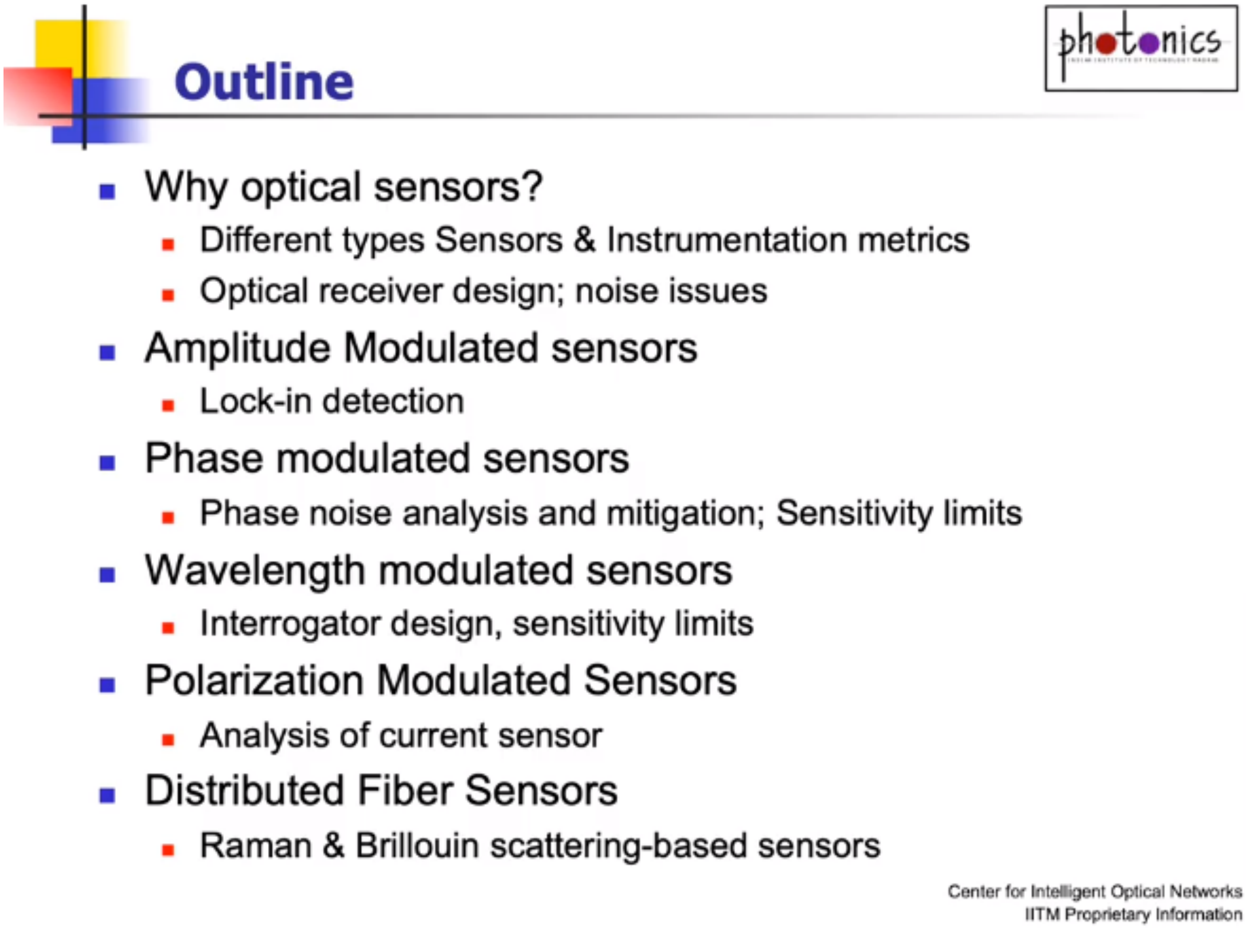
So, these are the different modules that we will consider. We will look at each of those type of sensors and we will see what are the challenges involved in that and how could you make if you wanted to make say, face modulated sensor, how could you make a face modulators sensor without getting external noise and without being affected by external noise and so on.

$$\mathbf{E(r,t)} = \mathbf{a_x} E_0 . exp[j(\omega t-\beta z)]$$



- Modulation in phase/frequency/amplitude/polarization
  - Due to changes in strain/temperature/pressure/rotation
  - Efficient demodulation is a key challenge

So, the course is going to consist of multiple modules and before I go to that, let me just also make a point that as we talked about in some of the previous applications, you may need to do distributed sensing as well that is actually picking up perturbations simultaneously happening from multiple points along this fiber. And we will see, what is that about?



So, let us just look at the course outline the overall plan for this course, we will start with, why optical sensors. So, what are the different types of optical sensors out there, what are the instrumentation metrics and one of the keys in any of these optical sensors is going to be the design of the optical receiver. So, we will go into the details of the construction of an optical receiver and while looking at those details, we will see that there are certain issues with respect to noise. We will see how we can handle that.

Then we will go on to different types of sensors, first we will look at amplitude modulated sensors. Then we will go on to phase modulators sensors, then wavelength modulated sensors and finally, polarization modulated sensors. So, these are the different types of sensors we will look at, examples we will look at case studies corresponding to each of those senses and what the typical issues there are.

And then finally, we will look at distributed fiber sensors like I said, these are very unique type of sensors because they are able to do something which almost no other sensor out there is able to do, which is get information over fairly long distances with very high precision, so that is actually the outline. So, then let us move into the specifics of the course.