Optical Fiber Sensors
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Lecture 42
Polarization Modulated Sensors-3

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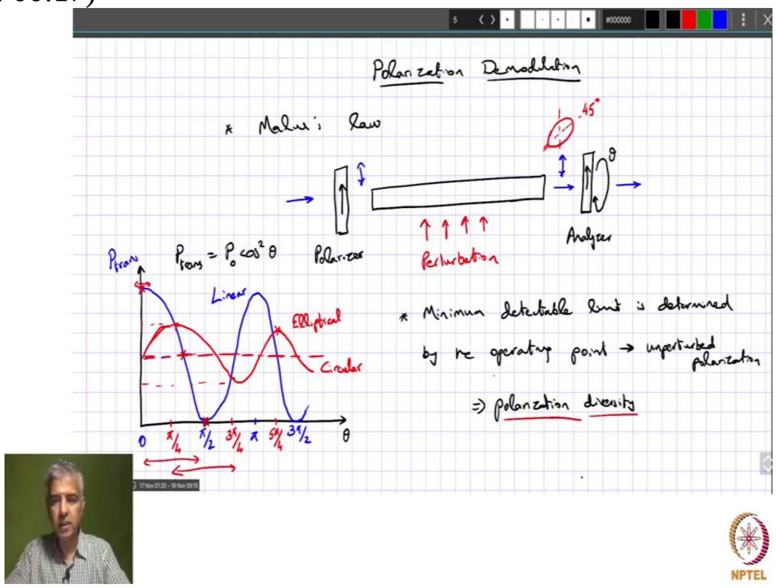

During the last lecture, we looked at the functionality of polarization demodulation as far as polarization modulated sensors are concerned. And we said it is typically accomplished by rotating an analyzer, but in several applications such moving parts are not desirable.

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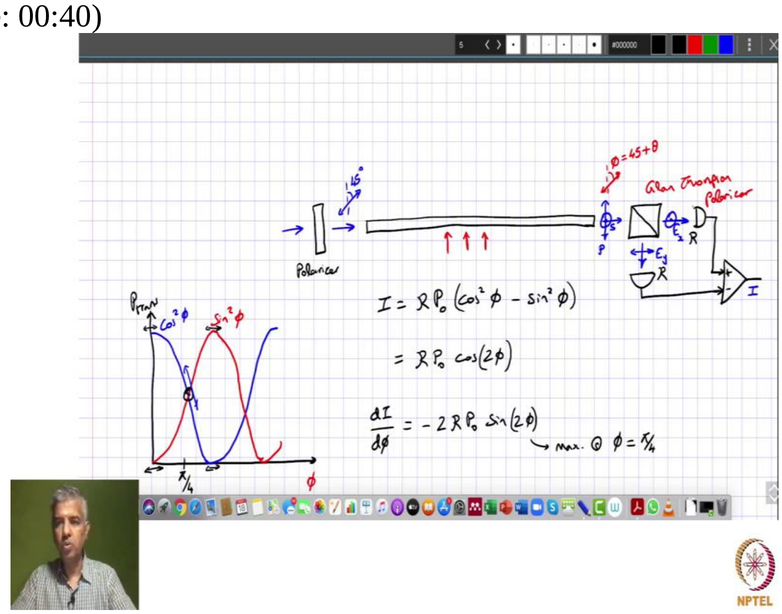

So, then we said we could possibly use a polarization splitter, and then do a balance detection, basically a differential detection to get an idea of how much rotation has happened, the polarization rotation has happened because of perturbation to the medium. And we also realize that it is best that we bias our incoming polarization at a 45-degree angle. So, that is where we get the maximum sensitivity.

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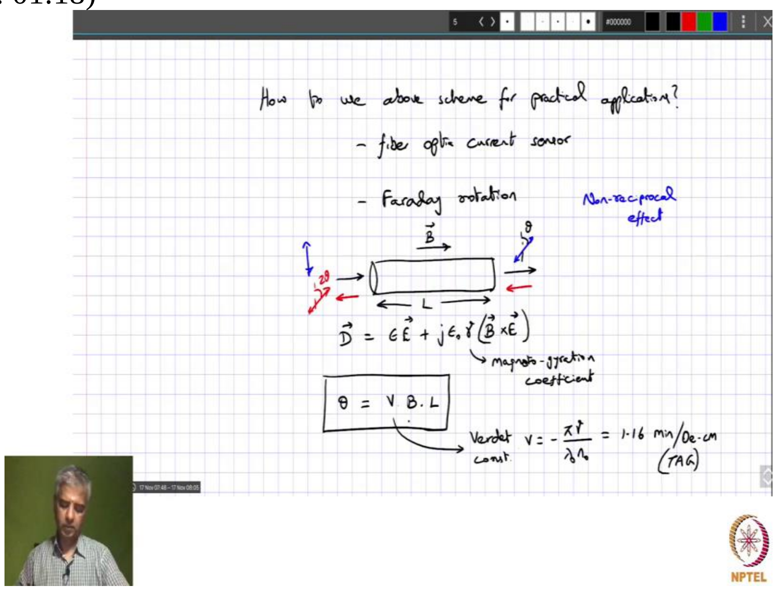

Then we went on to look at the example of fiber optic current sensor and we said, how can we achieve fiber optic current sensing through a polarization modulated sensor configuration. And the key to understanding that was the Faraday effect, which essentially said that, if you have a magnetic field axial oriented along the axis of a material and if that coincides with the propagation direction of an electromagnetic wave, then the polarization of that electromagnetic wave was going to get rotated by an angle theta which is defined by this expression over here.

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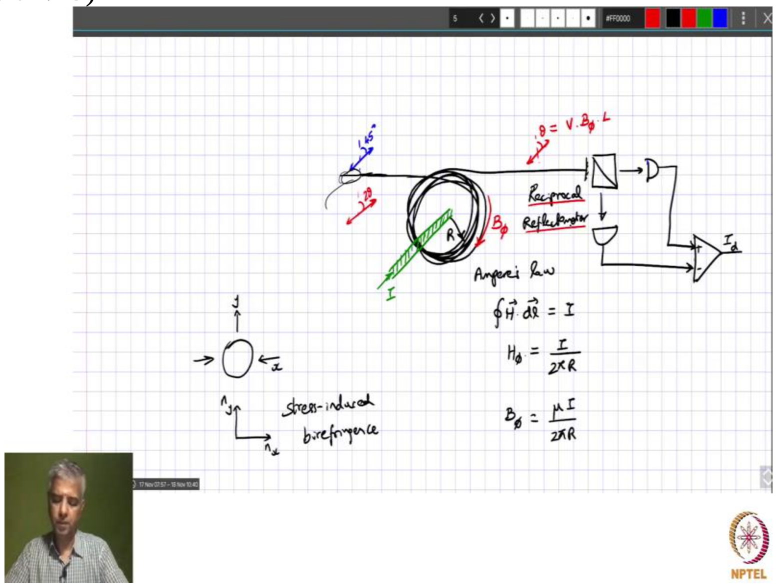

And so, that essentially says that, whenever you have a current carrying conductor, you will have a magnetic field developed around it, and that magnetic field can actually enable Faraday rotation. So, if you have an incoming polarization that is going to get rotated according to the level of current that you have. So, B phi can be actually replaced by I. So, the rotation is going to be proportional to the current and then of course, we could analyze using this balance detection scheme and figure out how much is that current.

And towards the end of the lecture, I was also mentioning the fact that, these fiber can be susceptible to environmental fluctuations vibrations and so, on, in which case, there will be what is called the stress induced birefringence. Essentially, if you look at the core of the optical fiber, if there is stress in one direction, then the refractive index, let us say this is this is along the y direction and this is along the x direction.

So, nx sorry, ny is now going to be different from nx and, because of that, you have what is called this stress induced birefringence which actually can cause some uncertainty in our measurement, because the stress induced birefringence would also tend to rotate your polarization. So, it would cause some confusion at the detection. Now, one way to get around it is by understanding that, this stress induced birefringence are completely reciprocally effect.

So, if you put a reflector over here and send it back, then it could actually (tra), it could trace back to the original polarization. Basically, it will cancel whatever random stress induced birefringence that you have in the fiber. Whereas if you look at the Faraday effect, the Faraday rotation specifically, on reflection, it is a Faraday affect is a non-reciprocal effect. So, upon reflection it will give you a further increase, it will actually double the angle of rotation compared to the single pass case.

So, we said this reciprocal reflectometer configuration is actually a very nice configuration for this current sensing application, because it completely takes out all this possible random polarization fluctuations. So, this is actually something that has been projected in the literature.

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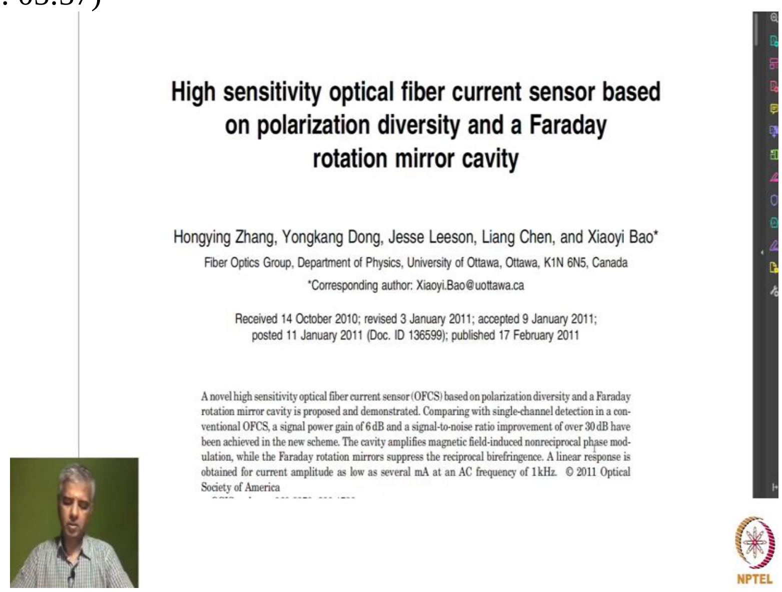

So, this is actually a paper that came in 2011. So, high sensitivity current sensor based on polarization diversity that is what we have been looking at with respect to a polarization beam splitter and they also talk about a Faraday rotation mirror, I will come back to that.

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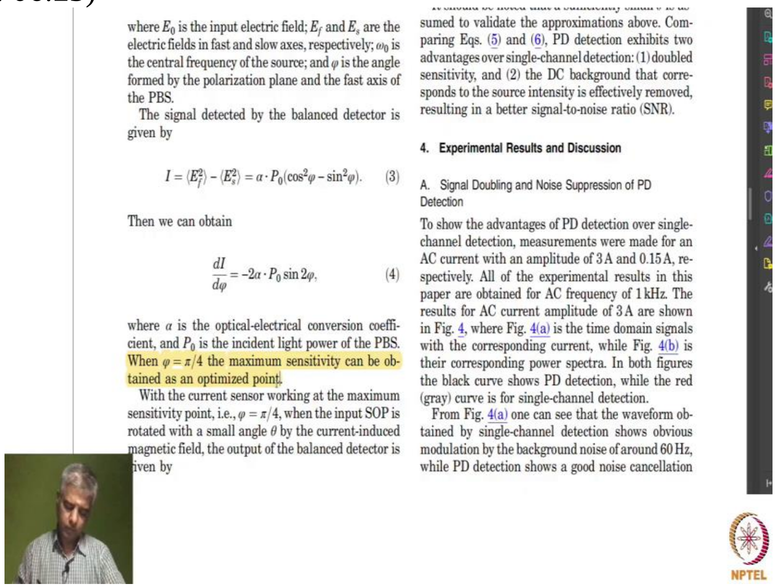

where E_0 is the input electric field; E_f and E_s are the electric fields in fast and slow axes, respectively; ω_0 is the central frequency of the source; and φ is the angle formed by the polarization plane and the fast axis of the PBS.

The signal detected by the balanced detector is given by

$$I = \langle E_f^2 \rangle - \langle E_s^2 \rangle = \alpha \cdot P_0(\cos^2\varphi - \sin^2\varphi). \quad (3)$$

Then we can obtain

$$\frac{dI}{d\varphi} = -2\alpha \cdot P_0 \sin 2\varphi, \quad (4)$$

where α is the optical-electrical conversion coefficient, and P_0 is the incident light power of the PBS. When $\varphi = \pi/4$ the maximum sensitivity can be obtained as an optimized point.

With the current sensor working at the maximum sensitivity point, i.e., $\varphi = \pi/4$, when the input SOP is rotated with a small angle θ by the current-induced magnetic field, the output of the balanced detector is given by

sumed to validate the approximations above. Comparing Eqs. (5) and (6), PD detection exhibits two advantages over single-channel detection: (1) doubled sensitivity, and (2) the DC background that corresponds to the source intensity is effectively removed, resulting in a better signal-to-noise ratio (SNR).

4. Experimental Results and Discussion

A. Signal Doubling and Noise Suppression of PD Detection

To show the advantages of PD detection over single-channel detection, measurements were made for an AC current with an amplitude of 3 A and 0.15 A, respectively. All of the experimental results in this paper are obtained for AC frequency of 1 kHz. The results for AC current amplitude of 3 A are shown in Fig. 4, where Fig. 4(a) is the time domain signals with the corresponding current, while Fig. 4(b) is their corresponding power spectra. In both figures the black curve shows PD detection, while the red (gray) curve is for single-channel detection.

From Fig. 4(a) one can see that the waveform obtained by single-channel detection shows obvious modulation by the background noise of around 60 Hz, while PD detection shows a good noise cancellation

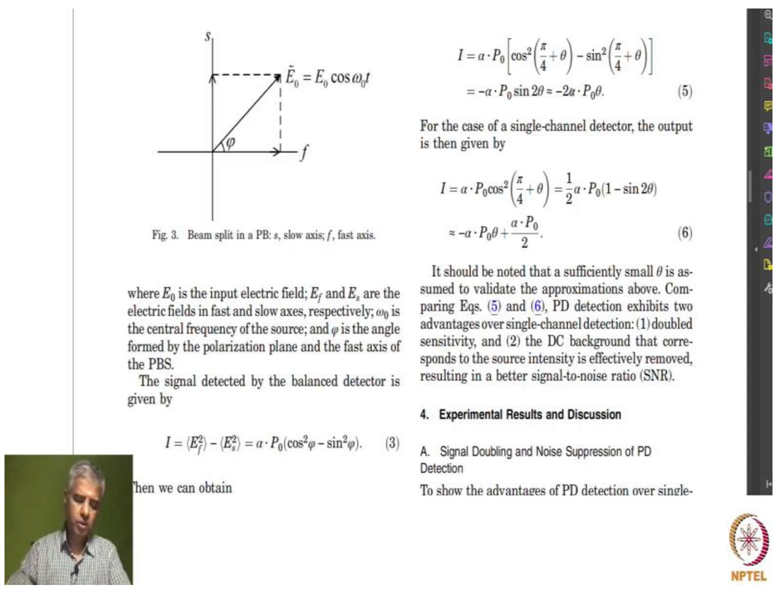

Fig. 3. Beam split in a PB: s, slow axis; f, fast axis.

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The signal detected by the balanced detector is given by

$$I = \langle E_f^2 \rangle - \langle E_s^2 \rangle = \alpha \cdot P_0(\cos^2\varphi - \sin^2\varphi). \quad (3)$$

Then we can obtain

$$I = \alpha \cdot P_0\left[\cos^2\left(\frac{\pi}{4}+\theta\right) - \sin^2\left(\frac{\pi}{4}+\theta\right)\right]$$
$$= -\alpha \cdot P_0 \sin 2\theta \approx -2\alpha \cdot P_0 \theta. \quad (5)$$

For the case of a single-channel detector, the output is then given by

$$I = \alpha \cdot P_0 \cos^2\left(\frac{\pi}{4}+\theta\right) = \frac{1}{2}\alpha \cdot P_0(1 - \sin 2\theta)$$
$$\approx -\alpha \cdot P_0 \theta + \frac{\alpha \cdot P_0}{2}. \quad (6)$$

It should be noted that a sufficiently small θ is as-

sumed to validate the approximations above. Comparing Eqs. (5) and (6), PD detection exhibits two advantages over single-channel detection: (1) doubled sensitivity, and (2) the DC background that corresponds to the source intensity is effectively removed, resulting in a better signal-to-noise ratio (SNR).

4. Experimental Results and Discussion

A. Signal Doubling and Noise Suppression of PD Detection

To show the advantages of PD detection over single-

But essentially, if you look at the, the math, so that is basically your balance detection that is your differential detection. And so, they say that the slope of change in the current with respect to the rotation angle is, going to be maximum at phi equal to pi by 4. So, that is what we have been looking at as well. And, and then, of course, they talk about, if you bias it at that point, then you get twice the angle, the rotation angle, because of this differential detection.

And they compare it with the case of a single channel, if it is only one channel, then you would essentially have only this current is proportional to theta but it also has this background, sort of a signal, that sort of a DC background, which is not desirable. So, in this case, there is no background over here, if you are doing this polarization diversity based detection. Whether we, alpha is what we have represented as the responsibility. So, that is not very different.

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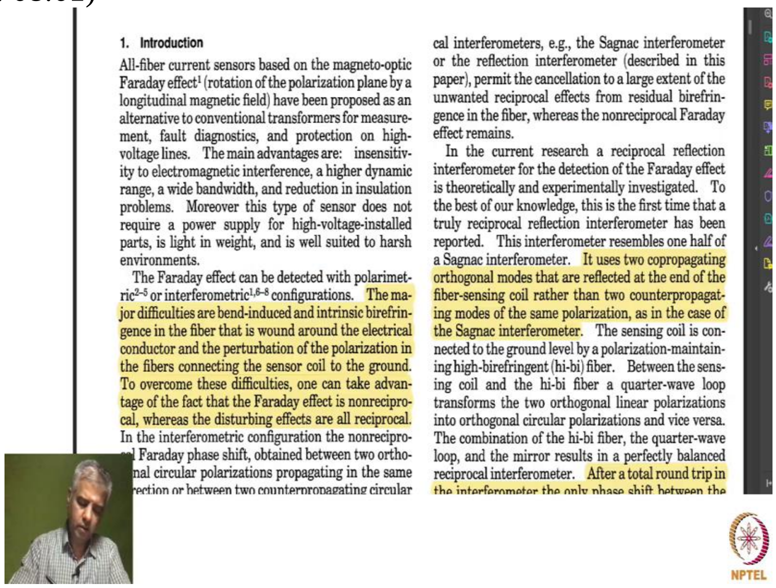


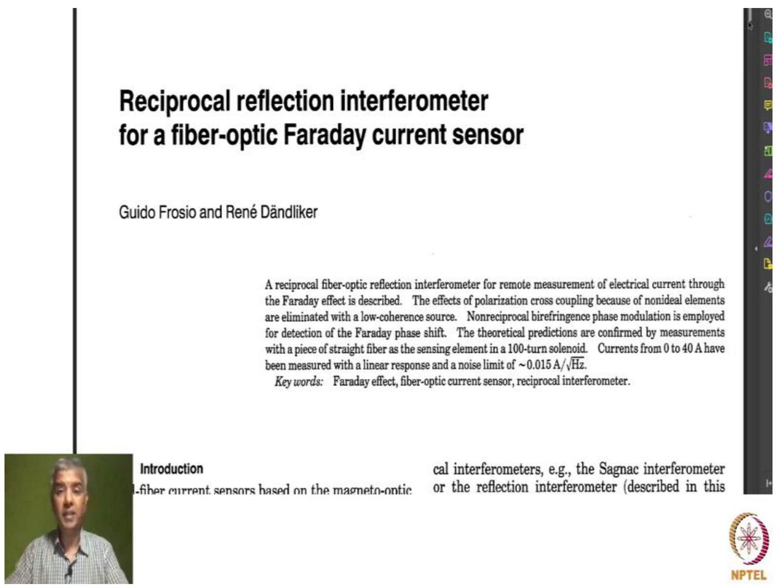
1. Introduction

All-fiber current sensors based on the magneto-optic Faraday effect[1] (rotation of the polarization plane by a longitudinal magnetic field) have been proposed as an alternative to conventional transformers for measurement, fault diagnostics, and protection on high-voltage lines. The main advantages are: insensitivity to electromagnetic interference, a higher dynamic range, a wide bandwidth, and reduction in insulation problems. Moreover this type of sensor does not require a power supply for high-voltage-installed parts, is light in weight, and is well suited to harsh environments.

The Faraday effect can be detected with polarimetric[2–5] or interferometric[1,6–8] configurations. The major difficulties are bend-induced and intrinsic birefringence in the fiber that is wound around the electrical conductor and the perturbation of the polarization in the fibers connecting the sensor coil to the ground. To overcome these difficulties, one can take advantage of the fact that the Faraday effect is nonreciprocal, whereas the disturbing effects are all reciprocal. In the interferometric configuration the nonreciprocal Faraday phase shift, obtained between two orthogonal circular polarizations propagating in the same direction or between two counterpropagating circular

cal interferometers, e.g., the Sagnac interferometer or the reflection interferometer (described in this paper), permit the cancellation to a large extent of the unwanted reciprocal effects from residual birefringence in the fiber, whereas the nonreciprocal Faraday effect remains.

In the current research a reciprocal reflection interferometer for the detection of the Faraday effect is theoretically and experimentally investigated. To the best of our knowledge, this is the first time that a truly reciprocal reflection interferometer has been reported. This interferometer resembles one half of a Sagnac interferometer. It uses two copropagating orthogonal modes that are reflected at the end of the fiber-sensing coil rather than two counterpropagating modes of the same polarization, as in the case of the Sagnac interferometer. The sensing coil is connected to the ground level by a polarization-maintaining high-birefringent (hi-bi) fiber. Between the sensing coil and the hi-bi fiber a quarter-wave loop transforms the two orthogonal linear polarizations into orthogonal circular polarizations and vice versa. The combination of the hi-bi fiber, the quarter-wave loop, and the mirror results in a perfectly balanced reciprocal interferometer. After a total round trip in the interferometer the only phase shift between the



Reciprocal reflection interferometer for a fiber-optic Faraday current sensor

Guido Frosio and René Dändliker

A reciprocal fiber-optic reflection interferometer for remote measurement of electrical current through the Faraday effect is described. The effects of polarization cross coupling because of nonideal elements are eliminated with a low-coherence source. Nonreciprocal birefringence phase modulation is employed for detection of the Faraday phase shift. The theoretical predictions are confirmed by measurements with a piece of straight fiber as the sensing element in a 100-turn solenoid. Currents from 0 to 40 A have been measured with a linear response and a noise limit of $\sim 0.015\ A/\sqrt{Hz}$.

Key words: Faraday effect, fiber-optic current sensor, reciprocal interferometer.

Introduction

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Of course, this entire scheme is originally proposed by Frosio back in 1994, so that is 26 years ago. So, they came up with this seminal paper in this area, where they recognized that using this reciprocal reflection interferometer configuration, it is actually a very highly sensitive way for doing current sensing.

And, and they clearly outlined that it is one of the major difficulties bend-induced an intrinsic birefringence in the fiber, that is the sensing coil. And to overcome this, we take advantage of the fact that the Faraday effect is non-reciprocal, whereas the disturbing effects are all reciprocal. So, that is where, they propose actually the first proposed in 1994, this reciprocal that reflection configuration.

And one of the things that they also mentioned is that we could essentially send two co propagating orthogonal modes. So, one way of looking at our cases is when you are at 45 degrees, you can say that there is actually a y component and an x component. So, they could be looking at that as two components that are co-propagating. And so that is what we have in our case, and it is reflected at the end of the fiber sensing coil.

And this is similar in certain way to Sagnac interferometer, only differences in a Sagnac interferometer we used to counterpropagating modes of the same polarization. So, there is some difference between what is happening in a Sagnac interferometer, and what is happening here in this reciprocal reflection configuration.

But you can see that the overall setup is actually going to look similar. So, and then of course, when we are talking about the reflection configuration after a round trip, what you have is the phase shift between two polarization caused by the Faraday effect. And that is important to understand as well.

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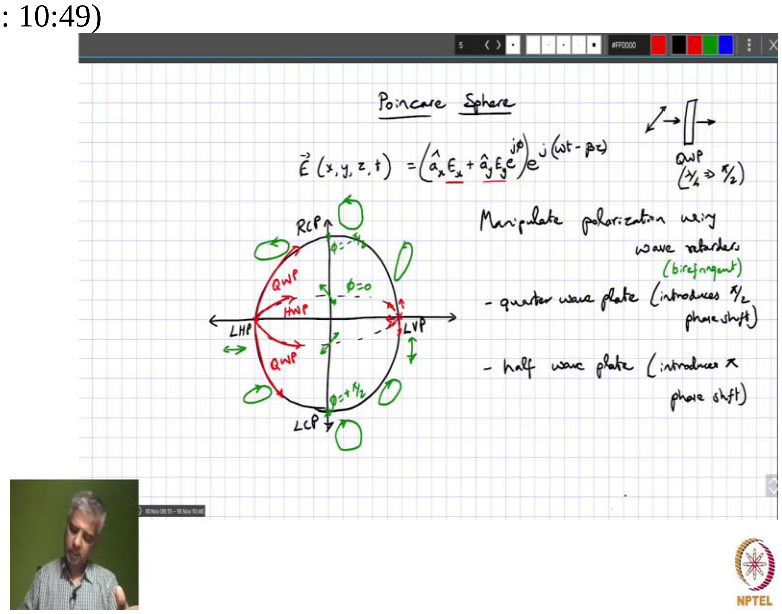

So, whenever we are looking at any change in polarization, that could be also, associated with the phase change between two orthogonal polarizations. So, in certain way we can measure phase change, the phase difference between the two orthogonal polarization, and that could be actually a good way of, of picking up changes in the state or the polarization.

So, that is actually saying that, although we say polarization modulated sensor in certain way, you can actually convert that to a phase modulated sensor. Because it is a phase retardation between two polarizations, that could actually be changed. And so if you are picking up the phase change between the two polarization that might actually do the job for you.

And that is what we are talking about the Faraday effect, if you send in two circularly, polarized orthogonally circularly polarized modes, let us say, left circularly polarized mode and right circularly polarized mode, as they undergo this Faraday rotation, or the Faraday effect. They actually have a phase shift between the two orthogonal polar circular polarization, and then we can now look at the phase shift between them.

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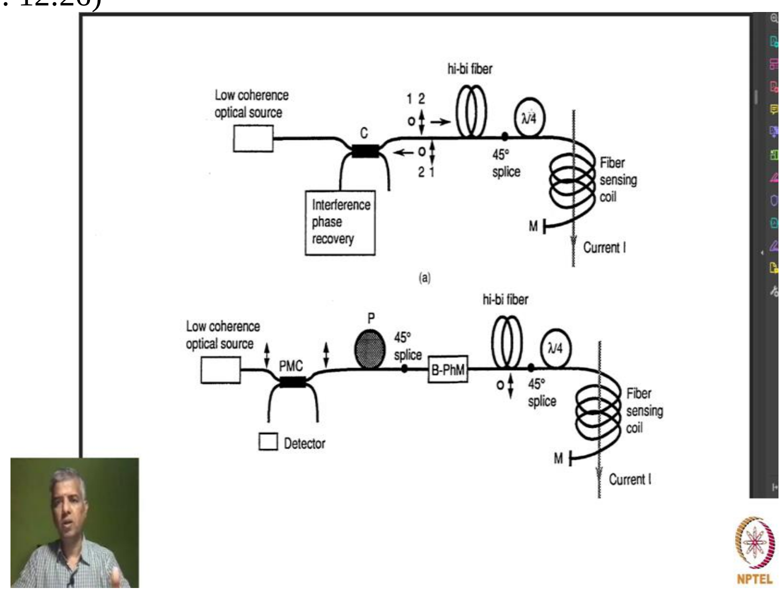

So, that is what is indicated over here. So, you start with a low coherence source, and you send it through a coupler, you launch it into, basically a hi-bi fiber, basically, if you want to do this sensing at a different point from the instrument, you want to preserve the polarization that is going through the fiber. So, you may want to use a highly birefringence fiber just to preserve the polarization state.

And then you go to a point where you have a 45-degree splice, and then you go through a quarter wave plate, we know that the 45 degree splice is actually just to make sure that your polarization launched into this quarter wave plate is at 45 degrees. And then if you go through a quarter wave plate, it converts into circular polarization. So, this linearly polarized radiation that is that corresponds to this vertical and horizontal components are going to get converted into left circular and right circular polarization states.

And those are the ones that are going through this fiber sensing coil. And at the end of it, you put a mirror so that it reflects it back. So, even as they propagate in the forward direction, the two polarize, orthogonally polarized states are going to have a phase shift between them. And that phase shift is going to only increase when you go through the reverse path. The that is, through the reflection.

And then once they come here, the quarter wave plate, once again converts from circular polarization back to linear polarization, this is something that we looked at over here. The quarter wave plate actually does these conversion. So, it will essentially convert from linear to circular but then circular back to linear as well. So, that is what is happening over here, it goes back to the linearly polarized state except that these two polarization now will have a phase shift between them.

And that phase shift corresponds to the current that you have in this conductor. So, essentially when you come back to your, when you tap that backward propagating light, and you look at an interferometer, where you can measure the relative ratio between the two polarization states, then that will actually be that phase shift is going to be proportional to the current in this conductor. So, that is what they proposed back in '94.

And that is something that is still followed except that when we go through these components, this coupler, the coupler, if it is not a polarization maintaining coupler, then this polarization state might change. So, that might actually change the phase between the relative phase between the two orthogonally polarized states. So, and you can of course, argue that I can make polarization maintaining coupler, but there again, that polarization maintaining coupler introduces an additional phase shift to these and that is actually an issue as well.

So, what you could possibly do is introduce a polarizer over here, and what this polarizer does is it basically on the reverse path it acts likes an analyzer. So, whatever phase shift that you have between the two polarization states that will, that will be converted to a intensity change beyond this.

So, instead of looking at phase detection, or doing a coherent detection you are actually looking at direct detection, where in this polarizer acts like an analyzer for the reverse path, and converts polarization changes into intensity changes. So, those are the typical configurations that we have been, that that could be looked at.

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current. Linear birefringence effects in the hi-bi fiber and twist-induced optical activity arising in the fiber between the loop and the mirror are canceled out because of the reciprocity of the interferometer. Figure 1(a) shows the principle of the reciprocal reflection interferometer used for Faraday effect detection.

The hi-bi fiber to the sensing head permits the placement of all detection and modulation elements at ground potential. At the interferometer output a polarizer causes the two output linear polarizations to interfere. The interference signal is proportional to $(1 + \cos 4\varphi_F)$ and therefore has a vanishing sensitivity to a weak Faraday effect. This problem can be overcome if the two linear polarizations are phase shifted by $\pi/2$ (quadrature detection) with a quarter-wave plate, for example. This phase shift can be achieved at the input of the interferometer before the coupler or at the output behind the coupler. The different parts of the interferometer, such as the sensing coil, the quarter-wave loop, and the hi-bi fiber, are not ideal and therefore introduce cross-coupling between the two propagating orthogonal modes. However, unlike the principal propagating modes, reciprocity is not realized for cross-coupled ...des. For example, if cross coupling arises in the ...sing coil, the cross-coupled part uses the same ...

performed in quadrature. The only way to solve this problem is to introduce a nonreciprocal phase shift inside the interferometer itself. The easiest way to produce an efficient nonreciprocal phase shift is to modulate periodically the relative phase of the two linear polarizations at the hi-bi fiber input with the help of a birefringence modulator. If the modulation period is equal to half of the time of flight for a total round trip, an optimum nonreciprocal relative phase modulation is obtained. In practice such a birefringence modulator can be realized with a hi-bi fiber wound around a piezoceramic stretcher[9]; integrated-optic modulators are also good candidates. The resulting interference is similar to the one obtained with classical nonreciprocal phase modulation for fiber gyroscopes; therefore the same signal processing can be used.

In conclusion our reflection interferometer is reciprocal, as the Sagnac interferometer is. However, for it to achieve a similar performance requires only one quarter-wave loop and half of the number of splices, which is important for practical current sensor realizations. Moreover its sensitivity to the Faraday effect is twice as high as for the Sagnac interferometer; thus for the same sensitivity a sensing coil with half of the number of turns can be used, ensuring ...

And of course, if you read some of the details of this, we say that typically if you just send a two linear polarization, then that will have a vanishing effect. Because essentially, at the end of it, we are looking at the interference signal and interference between the two polarization. So, it will have a very weak signal, if it is biased at exactly at the linear polarization.

So, what we are looking at is instead of sending linear polarization, you do quadrature detection with a quarter wave plate. Basically, that is what we talked about, we launch a circular polarization. So, those are some details that you can go through, but hopefully, you get an idea of what, how current sensing is accomplished through this reciprocal reflection configuration.

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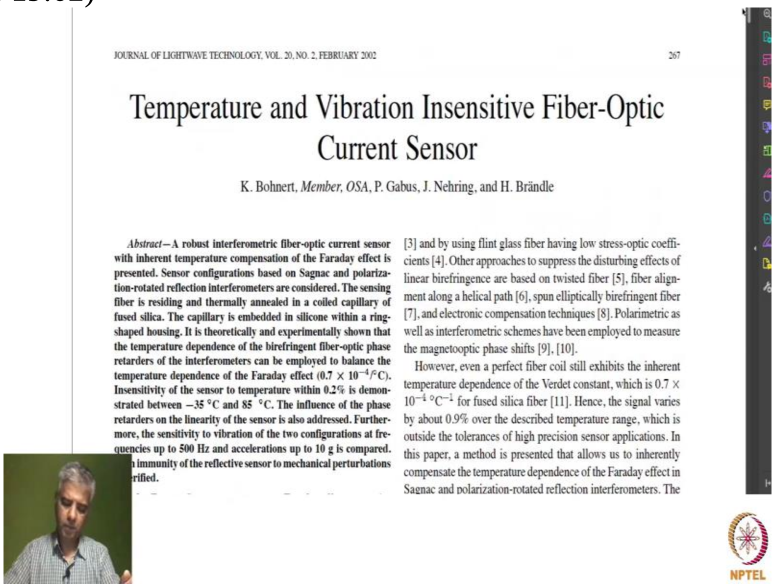


JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 20, NO. 2, FEBRUARY 2002 267

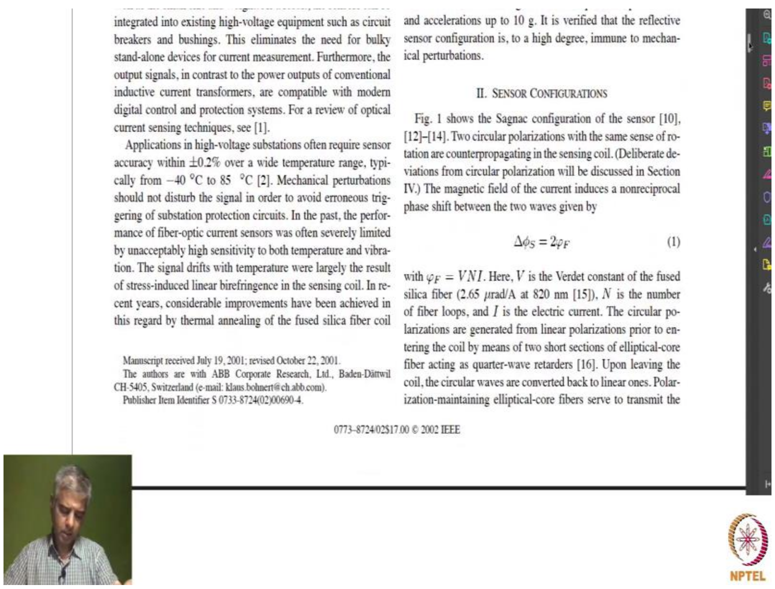
Temperature and Vibration Insensitive Fiber-Optic Current Sensor

K. Bohnert, *Member, OSA*, P. Gabus, J. Nehring, and H. Brändle

***Abstract*—A robust interferometric fiber-optic current sensor with inherent temperature compensation of the Faraday effect is presented. Sensor configurations based on Sagnac and polarization-rotated reflection interferometers are considered. The sensing fiber is residing and thermally annealed in a coiled capillary of fused silica. The capillary is embedded in silicone within a ring-shaped housing. It is theoretically and experimentally shown that the temperature dependence of the birefringent fiber-optic phase retarders of the interferometers can be employed to balance the temperature dependence of the Faraday effect (0.7×10^{-4}/°C). Insensitivity of the sensor to temperature within 0.2% is demonstrated between −35 °C and 85 °C. The influence of the phase retarders on the linearity of the sensor is also addressed. Furthermore, the sensitivity to vibration of the two configurations at frequencies up to 500 Hz and accelerations up to 10 g is compared. ...h immunity of the reflective sensor to mechanical perturbations ...rified.**

[3] and by using flint glass fiber having low stress-optic coefficients [4]. Other approaches to suppress the disturbing effects of linear birefringence are based on twisted fiber [5], fiber alignment along a helical path [6], spun elliptically birefringent fiber [7], and electronic compensation techniques [8]. Polarimetric as well as interferometric schemes have been employed to measure the magnetooptic phase shifts [9], [10].

However, even a perfect fiber coil still exhibits the inherent temperature dependence of the Verdet constant, which is 0.7×10^{-4} °C^{-1} for fused silica fiber [11]. Hence, the signal varies by about 0.9% over the described temperature range, which is outside the tolerances of high precision sensor applications. In this paper, a method is presented that allows us to inherently compensate the temperature dependence of the Faraday effect in Sagnac and polarization-rotated reflection interferometers. The



integrated into existing high-voltage equipment such as circuit breakers and bushings. This eliminates the need for bulky stand-alone devices for current measurement. Furthermore, the output signals, in contrast to the power outputs of conventional inductive current transformers, are compatible with modern digital control and protection systems. For a review of optical current sensing techniques, see [1].

Applications in high-voltage substations often require sensor accuracy within ±0.2% over a wide temperature range, typically from −40 °C to 85 °C [2]. Mechanical perturbations should not disturb the signal in order to avoid erroneous triggering of substation protection circuits. In the past, the performance of fiber-optic current sensors was often severely limited by unacceptably high sensitivity to both temperature and vibration. The signal drifts with temperature were largely the result of stress-induced linear birefringence in the sensing coil. In recent years, considerable improvements have been achieved in this regard by thermal annealing of the fused silica fiber coil

Manuscript received July 19, 2001; revised October 22, 2001.
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Publisher Item Identifier S 0733-8724(02)00690-4.

and accelerations up to 10 g. It is verified that the reflective sensor configuration is, to a high degree, immune to mechanical perturbations.

II. Sensor Configurations

Fig. 1 shows the Sagnac configuration of the sensor [10], [12]–[14]. Two circular polarizations with the same sense of rotation are counterpropagating in the sensing coil. (Deliberate deviations from circular polarization will be discussed in Section IV.) The magnetic field of the current induces a nonreciprocal phase shift between the two waves given by

$$\Delta\phi_S = 2\varphi_F \quad (1)$$

with $\varphi_F = VNI$. Here, V is the Verdet constant of the fused silica fiber (2.65 μrad/A at 820 nm [15]), N is the number of fiber loops, and I is the electric current. The circular polarizations are generated from linear polarizations prior to entering the coil by means of two short sections of elliptical-core fiber acting as quarter-wave retarders [16]. Upon leaving the coil, the circular waves are converted back to linear ones. Polarization-maintaining elliptical-core fibers serve to transmit the

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Now, this is of course, being taken up and this technology now commercialized. And for example, we look at this paper by Bohnert and et al. And so, they are actually working with ABB, actually, it is a major company working in this domain, in electrical power industry.

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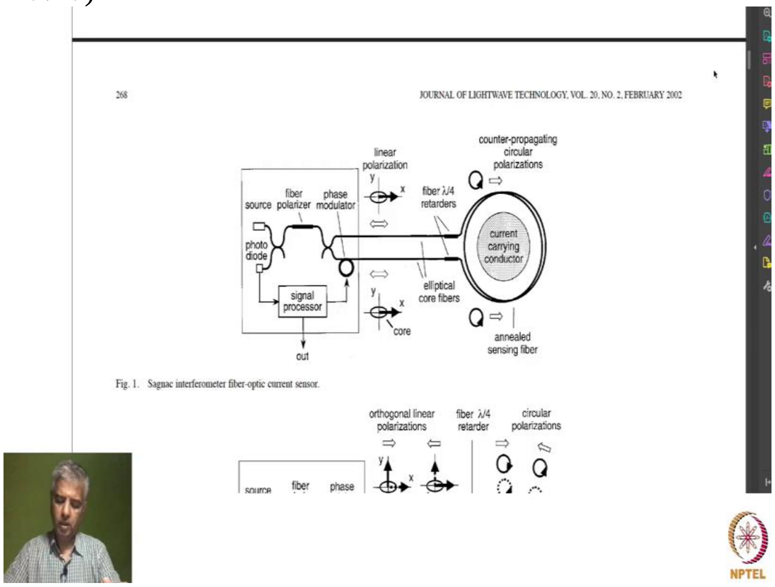

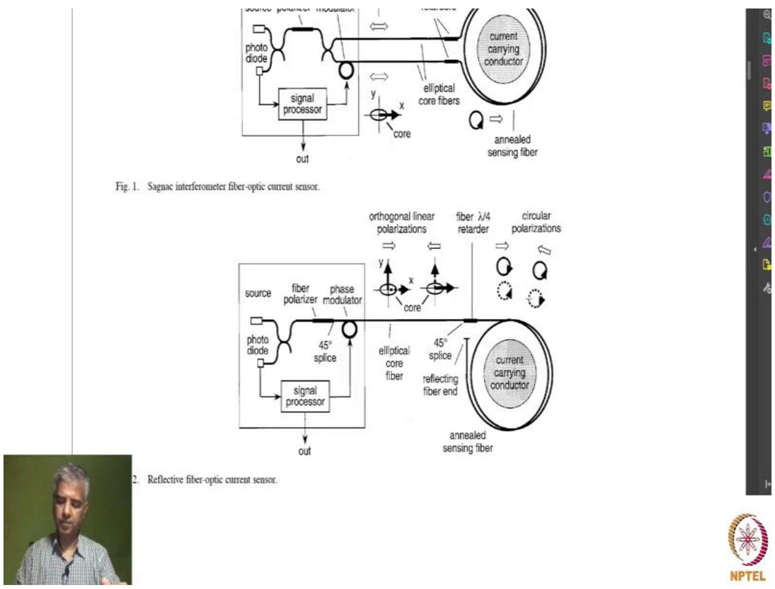

And so, they also have adopted a similar type of configuration, this reflection configuration and they show that basically there is going to be a phase shift between the two circular polarizations because of this Faraday affect and then they talk about how to demodulate using this fiber polarizer and then pick up intensity changes corresponding to phase change.

So, in certain ways, like it is similar to Sagnac interferometers. So, some of the in the configuration looks similar to Sagnac interferometer. So, some of the things that we implement there with respect to modulating the face, so that you can do like a phase generated carrier detection, you can do that also here and that will improve the sensitivity and also use a low coherence source typically, so, that any coherent rally, back scatter is not actually introducing uncertainty, the measurement and so on. So, there are some interesting things to note here.

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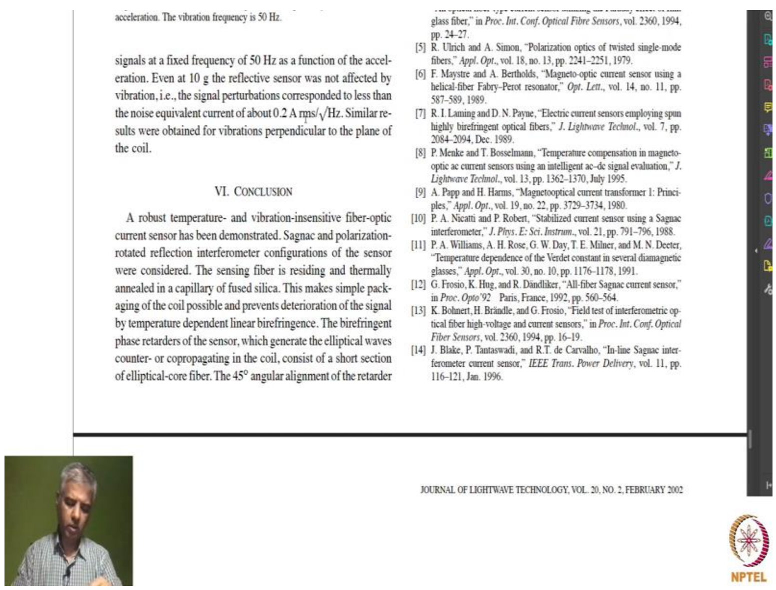

acceleration. The vibration frequency is 50 Hz.

signals at a fixed frequency of 50 Hz as a function of the acceleration. Even at 10 g the reflective sensor was not affected by vibration, i.e., the signal perturbations corresponded to less than the noise equivalent current of about 0.2 A rms/$\sqrt{Hz}$. Similar results were obtained for vibrations perpendicular to the plane of the coil.

VI. Conclusion

A robust temperature- and vibration-insensitive fiber-optic current sensor has been demonstrated. Sagnac and polarization-rotated reflection interferometer configurations of the sensor were considered. The sensing fiber is residing and thermally annealed in a capillary of fused silica. This makes simple packaging of the coil possible and prevents deterioration of the signal by temperature dependent linear birefringence. The birefringent phase retarders of the sensor, which generate the elliptical waves counter- or copropagating in the coil, consist of a short section of elliptical-core fiber. The 45° angular alignment of the retarder

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But the key point is finally, they managed to package their sensing coil in such a manner. So, this is what is going to go over this conductor, which is carrying this high current level. So, and that has been actually shown to be very good over a wide range of current levels and, it gives a noisy equivalent current of 0.2 amperes RMS per root hertz. So, it can achieve very good performance with such current sensors.

So, that is looking at a fiber optic current sensor as an example of polarization modulated sensor, and that is actually happening at a, at one particular location. So, or whatever we were looking at is, monitoring current at one particular location. But if there is a requirement to monitor current over wide over a long region in a distributed manner, you could use what is called a polarization OTDR and this is a concept that was first introduced back in 1981.

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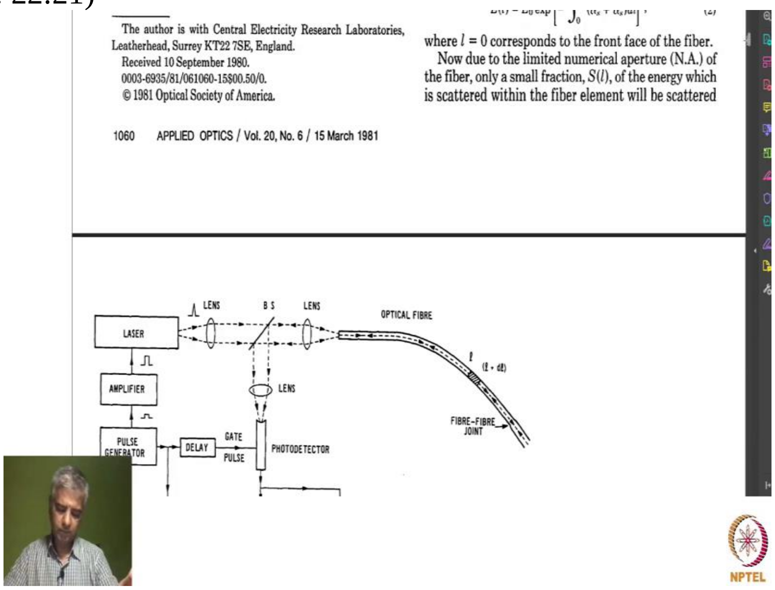
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Received 10 September 1980.
0003-6935/81/061060-15$00.50/0.
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where $l = 0$ corresponds to the front face of the fiber.
Now due to the limited numerical aperture (N.A.) of the fiber, only a small fraction, $S(l)$, of the energy which is scattered within the fiber element will be scattered

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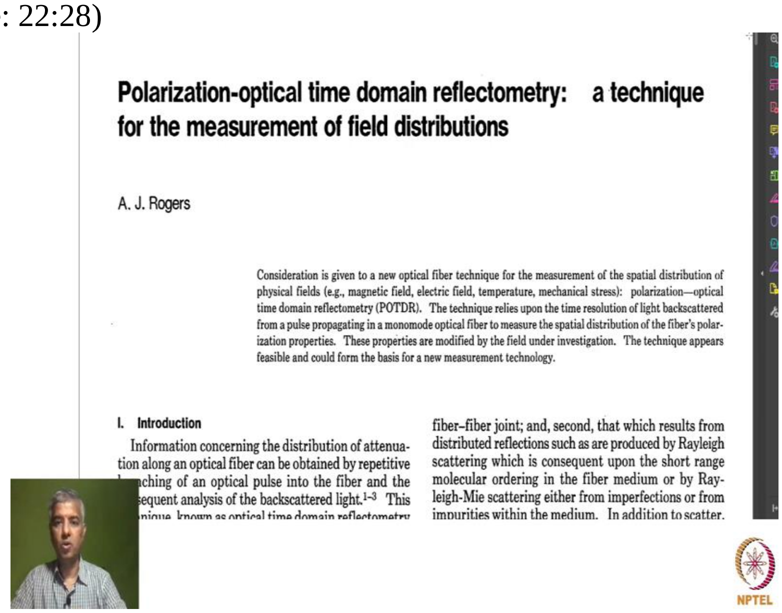
Polarization-optical time domain reflectometry: a technique for the measurement of field distributions

A. J. Rogers

Consideration is given to a new optical fiber technique for the measurement of the spatial distribution of physical fields (e.g., magnetic field, electric field, temperature, mechanical stress): polarization—optical time domain reflectometry (POTDR). The technique relies upon the time resolution of light backscattered from a pulse propagating in a monomode optical fiber to measure the spatial distribution of the fiber's polarization properties. These properties are modified by the field under investigation. The technique appears feasible and could form the basis for a new measurement technology.

I. Introduction

Information concerning the distribution of attenuation along an optical fiber can be obtained by repetitive ...nching of an optical pulse into the fiber and the ...sequent analysis of the backscattered light.[1-3] This ...nique known as optical time domain reflectometry

fiber–fiber joint; and, second, that which results from distributed reflections such as are produced by Rayleigh scattering which is consequent upon the short range molecular ordering in the fiber medium or by Rayleigh-Mie scattering either from imperfections or from impurities within the medium. In addition to scatter-

So, this is actually march of 1981 (())(22:25) perspective optical fibers, started becoming, started becoming available only around that time, in the late 70s and 80s commercially. And so, even as the optical fiber became available, they started research with sensing. So, they did optical time domain reflectometry in 1981. And, to top that they also, Alan Rogers actually also introduced this concept of polarization, optical time domain reflectometry several decades ago, four decades ago, that is, that is quite amazing.

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III. Polarization-Optical Time Domain Reflectometry (POTDR)

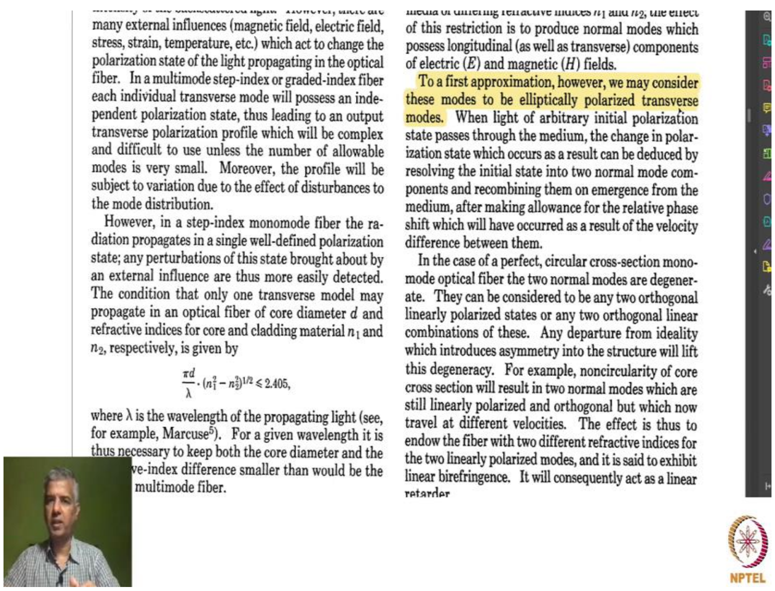
A. Introduction

The OTDR technique which we have been considering makes use only of the information contained in the intensity of the backscattered light. However, there are many external influences (magnetic field, electric field, stress, strain, temperature, etc.) which act to change the polarization state of the light propagating in the optical fiber. In a multimode step-index or graded-index fiber each individual transverse mode will possess an independent polarization state, thus leading to an output transverse polarization profile which will be complex and difficult to use unless the number of allowable modes is very small. Moreover, the profile will be subject to variation due to the effect of disturbances to ... de distribution.

...ver, in a step-index monomode fiber the ra-

lipticity but with their major axes orthogonal. The electric vector rotates in opposite directions for the two modes, and they have different propagation velocities. In a circular monomode waveguide an extra restriction on the propagation is provided by the boundary conditions constituted by the surface separating the two media of differing refractive indices n_1 and n_2; the effect of this restriction is to produce normal modes which possess longitudinal (as well as transverse) components of electric (E) and magnetic (H) fields.

To a first approximation, however, we may consider these modes to be elliptically polarized transverse modes. When light of arbitrary initial polarization state passes through the medium, the change in polarization state which occurs as a result can be deduced by resolving the initial state into two normal mode components and recombining them on emergence from the medium, after making allowance for the relative phase shift which will have occurred as a result of the velocity


many external influences (magnetic field, electric field, stress, strain, temperature, etc.) which act to change the polarization state of the light propagating in the optical fiber. In a multimode step-index or graded-index fiber each individual transverse mode will possess an independent polarization state, thus leading to an output transverse polarization profile which will be complex and difficult to use unless the number of allowable modes is very small. Moreover, the profile will be subject to variation due to the effect of disturbances to the mode distribution.

However, in a step-index monomode fiber the radiation propagates in a single well-defined polarization state; any perturbations of this state brought about by an external influence are thus more easily detected. The condition that only one transverse model may propagate in an optical fiber of core diameter d and refractive indices for core and cladding material n_1 and n_2, respectively, is given by

$$\frac{\pi d}{\lambda} \cdot (n_1^2 - n_2^2)^{1/2} \leq 2.405,$$

where λ is the wavelength of the propagating light (see, for example, Marcuse[5]). For a given wavelength it is thus necessary to keep both the core diameter and the ...ve-index difference smaller than would be the ... multimode fiber.

of this restriction is to produce normal modes which possess longitudinal (as well as transverse) components of electric (E) and magnetic (H) fields.

To a first approximation, however, we may consider these modes to be elliptically polarized transverse modes. When light of arbitrary initial polarization state passes through the medium, the change in polarization state which occurs as a result can be deduced by resolving the initial state into two normal mode components and recombining them on emergence from the medium, after making allowance for the relative phase shift which will have occurred as a result of the velocity difference between them.

In the case of a perfect, circular cross-section monomode optical fiber the two normal modes are degenerate. They can be considered to be any two orthogonal linearly polarized states or any two orthogonal linear combinations of these. Any departure from ideality which introduces asymmetry into the structure will lift this degeneracy. For example, noncircularity of core cross section will result in two normal modes which are still linearly polarized and orthogonal but which now travel at different velocities. The effect is thus to endow the fiber with two different refractive indices for the two linearly polarized modes, and it is said to exhibit linear birefringence. It will consequently act as a linear retarder

But, anyway, in this paper he talks about, first of all, how to accomplish OTDR that is the first part of the paper, but then it goes into polarization optical domain reflectometry. And essentially, you consider that light polarization to be elliptically polarized. So, whatever is back reflected, you look at it as, and the back reflection is because of rally scattering in the fiber.

But you look at it, you model that as a elliptically polarized, and that is actually good reason, because, you start with the generic definition, and then you say the ellipticity, the aspect ratio goes to infinity, which means that one component is missing, the other component is prominent that is what we will consider as a linear polarization or of the ellipticity the aspect ratio equal to 1, that will mean that both the components x and y components are equal and then that becomes a circular polarization. So, if you model it as an elliptically polarized wave, then it that can actually capture whatever is happening as far as other polarization states are concerned.

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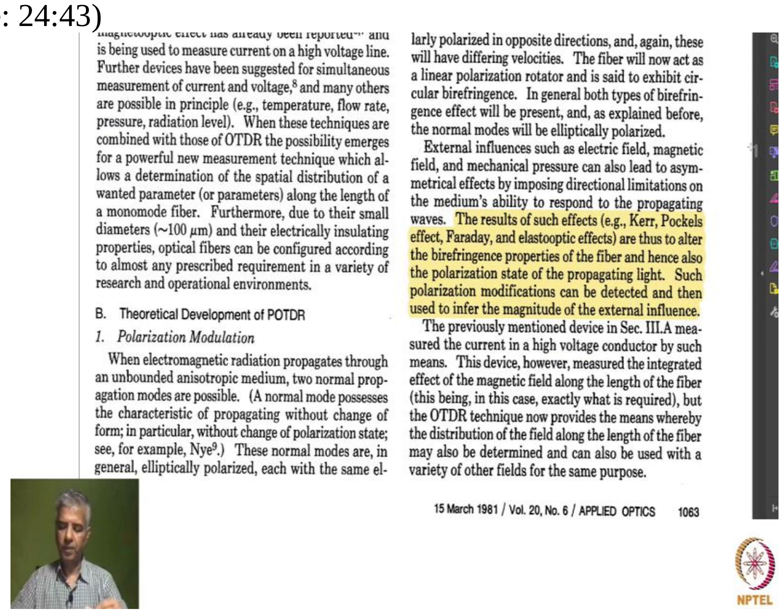
magnetooptic effect has already been reported and is being used to measure current on a high voltage line. Further devices have been suggested for simultaneous measurement of current and voltage,[8] and many others are possible in principle (e.g., temperature, flow rate, pressure, radiation level). When these techniques are combined with those of OTDR the possibility emerges for a powerful new measurement technique which allows a determination of the spatial distribution of a wanted parameter (or parameters) along the length of a monomode fiber. Furthermore, due to their small diameters (~100 μm) and their electrically insulating properties, optical fibers can be configured according to almost any prescribed requirement in a variety of research and operational environments.

B. Theoretical Development of POTDR

1. Polarization Modulation

When electromagnetic radiation propagates through an unbounded anisotropic medium, two normal propagation modes are possible. (A normal mode possesses the characteristic of propagating without change of form; in particular, without change of polarization state; see, for example, Nye[9].) These normal modes are, in general, elliptically polarized, each with the same ellarly polarized in opposite directions, and, again, these will have differing velocities. The fiber will now act as a linear polarization rotator and is said to exhibit circular birefringence. In general both types of birefringence effect will be present, and, as explained before, the normal modes will be elliptically polarized.

External influences such as electric field, magnetic field, and mechanical pressure can also lead to asymmetrical effects by imposing directional limitations on the medium's ability to respond to the propagating waves. The results of such effects (e.g., Kerr, Pockels effect, Faraday, and elastooptic effects) are thus to alter the birefringence properties of the fiber and hence also the polarization state of the propagating light. Such polarization modifications can be detected and then used to infer the magnitude of the external influence.

The previously mentioned device in Sec. III.A measured the current in a high voltage conductor by such means. This device, however, measured the integrated effect of the magnetic field along the length of the fiber (this being, in this case, exactly what is required), but the OTDR technique now provides the means whereby the distribution of the field along the length of the fiber may also be determined and can also be used with a variety of other fields for the same purpose.

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And it is interesting that a lot of these effects like Kerr effect, which is based on the light intensity, the light intensity changing the refractive index of the medium the Pockels effect which is dependent on an externally applied electric field changing the refractive index of the medium. The Faraday effect, we saw how a Faraday effect is actually corresponding to an externally applied magnetic field changing the state of polarization and you could also think of other elasto optic effects.

All these alter the birefringence properties of the fiber and hence the polarization state of the propagating light. So, such polarization modifications can be detected to infer the magnitude of the external influence. So, you can think of something like simply measuring strain or temperature changes or you could measure electric field or magnetic field as quantities and or you could even measure some vibrations, we talked about intrusion detection from a perspective of phase modulated sensor and, back we were talking about distributed acoustic sensing and we said it could be useful for intrusion detection.

Now, the same thing can be considered here as well, because any vibrations are going to end up perturbing the fiber and that will cause a change in the polarization. And by looking at polarization changes, you can actually infer, how much is the, what type of perturbation the fiber is getting subjected to? And of course, we are marrying the polarization modulators sensor with optical time domain reflectometry to achieve this polarization OTDR.

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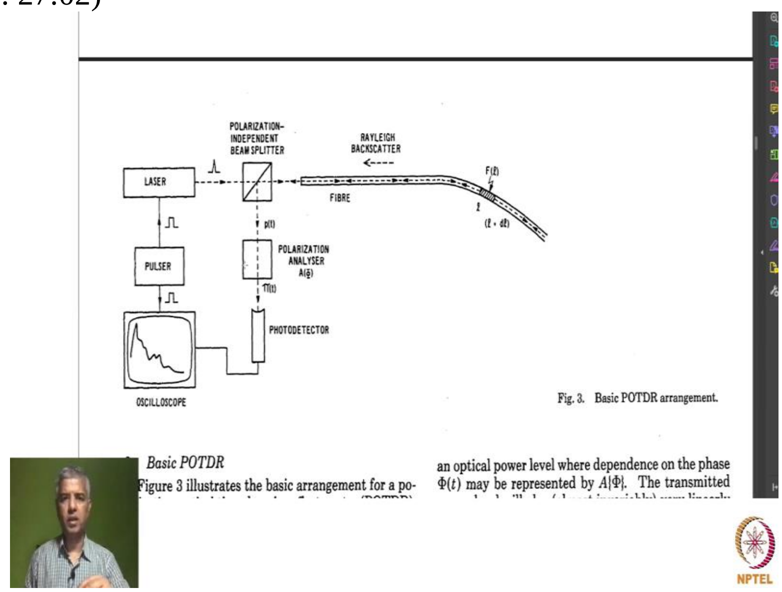

So, at the end of it, what you need is in the back reflected light you need to do a polarization analysis. So, previously we were either doing just say intensity analysis or a phase analysis, but now we are actually looking at polarization analysis. And of course, we looked at Brillouin sensors where we are doing a frequency analysis in that case, but as far as the polarization modulators sensor is concerned we do a polarization analysis which could involve actually doing a relative phase analysis between the two orthogonal polarized components.

And that could also give you some idea of the kind of perturbation that has happened over here. So, in some ways you can say phase modulator sensors and polarization modulators sensors there is some meeting point between them, in other words polarization modulators sensor can be simply looked upon as a phase modulated sensor where we are looking at the phase between the two orthogonal components in this case. So, that is pretty much what I wanted to convey as far as polarization modulators sensors go.

So, let us just go back here. And so, we come to a point where, we have gone a long way as far as this course is concerned. So, let us actually do a quick recap of what we have done overall in this course. So, we started all the way from basic definition of an optical sensor, and we identified that you need to have a source, you need to have a receiver and you may need some demodulation mechanism.

But, you are trying to actually pick up changes in amplitude phase, wavelength or polarization. And then we started going back and looking at optical sources and then optical detectors. Then, we started considering noise in optical detectors. We started considering the receiver design, the optical receiver design and then we looked at the noise on optical receivers overall.

And from there, we went on to looking at quantifying the performance metrics of our sensors in terms of the measurement range, the minimum detection limit, the sensitivity response time and accuracy as well as precision we understood what these quantities mean. And then we started looking at how to mitigate noise in your measurement. What are the common ways of doing that we looked at averaging, we looked at filtering, and then we looked at lock-in detection.

And with that sort of information, we were, starting to look at amplitude modulated sensors. And amplitude modulated sensors are the simplest ones, because there is no demodulation mechanism, that is necessary, your optical receiver can directly pick up changes in amplitude or intensity.

And we looked at examples of that. For example, we looked at this differential absorption spectroscopy and how it can be accomplished in a, in a fiber sensor. And then we looked at another example, which is pulse oximetry. Once again, we are looking at differential absorption spectroscopy in this case, and then we said you may want to do the sensing in a distributed manner. So, in which case you can actually go for an optical time domain reflectometry, we looked at the basic principles as far as OTDRs are concerned.

And the trade-off between spatial resolution and the signal to noise ratio that you can get from your detection. And then we looked at some specific examples of a design of amplitude modulated sensor once again for a gas spectroscopy application. And then we went on to look at phase modulated sensors and we said instead of picking up changes in amplitude, you could pick up changes in phase and we recognize that phase modulated sensors are quite sensitive to perturbations. So, the phase is actually quite sensitive to perturbations.

And then we looked at examples of phase modulators. So, we said, but phase is not directly picked up by a receiver. So, we needed an interferometer configuration to do the demodulation of phase to intensity changes. And one such example of the Michelson interferometer, which we started looking at an example of using that for optical coherence tomography. And we learned that there are several challenges as far as phase modulated sensors are concerned and we looked at how to overcome some of these challenges.

So, we spent quite a bit of time learning this phase generated carrier technique for overcoming environmentally induced noise and doing a lock-in detection with respect to that looked at phase noise and optical sources. And, then we looked at another example, which is fiber optic gyroscope is based on this Sagnac interferometer. So, we spent a bit of time understanding how phase modulated sensor that can be implemented in the Sagnac configuration. And that could be useful for looking at fiber optic gyroscopes, the challenges in that and the performance limitations.

And then we looked at combining a phase modulated sensor with an OTDR to do distributed sensing. So in this case, we looked at distributed acoustic sensing. And we realized that it may not be good to pick up absolute phase over long distances because of phase is evolving rapidly and it is susceptible to a lot of noise. But, it could be very good to pick up specific frequencies like acoustic frequencies. So, that is what we looked at.

And then we went on to looking at wavelength modulated sensors, and we said wavelength modulators sensors are very robust to external perturbations, while propagation because the wavelength information once the whatever perturbation that we are interested in is encoded into change in wavelength, that change in wavelength is not going to be corrupted by any of the conventional noise sources.

So, and we looked at the example of using a fiber Bragg grating for doing the sensing, we looked at what are the challenges, as far as that is concerned, we looked at specific examples, and then, we looked at how we can pick up changes in wavelength that is that is the integration of FBGs. We looked at various schemes as far as wavelength demodulation is concerned.

And we said basically, for static cases or quasi static sensing a spectrum analysis is a very good approach especially if you want to do quasi distributed type of sensing over a long region. But, if you have only a requirement to for localized sensing, but you need to do that at much higher frequencies, we said the match filter technique can be quite useful. So, we looked at the performance limits of doing such sensing.

And then we said one more if you wanted to do frequency modulation sensing or wavelength modulated sensing over long distances, that can be achieved using the stimulator Brillouin scattering phenomena. And we saw how changes in strain or temperature will cause a change in the acoustic velocity and based on that the Brillouin scattered frequencies will be changing. And we learned how to pick up that Brillouin frequency.

And then we recently came to polarization modulated sensors, where again, we said that any perturbation to the propagation of electromagnetic wave can cause a change in the polarization of light and once again demodulation is a challenge. And we looked at the possibility of doing demodulation using a simple analyzer then going to a polarization diversity scheme.

And we looked at the example of how this is performed using a fiber optic current sensor. And finally, we also looked at today, how this polarization modulated sensor concept can be married with OTDR to accomplish distributed sensing as well. So, with that, we are completing the course.

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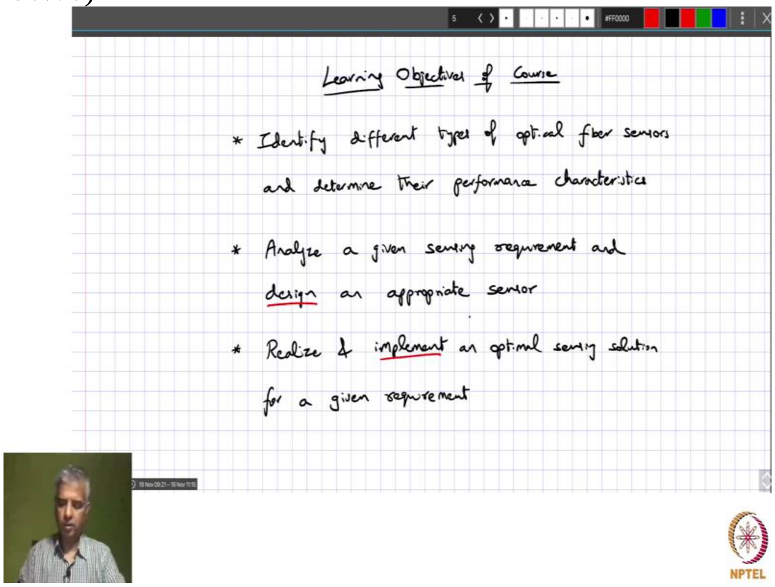

So, let us actually ask some bigger questions about what this course has meant. What were the learning objectives of the course, actually from my perspective, and hopefully you agree with that, first objective was to identify different types of optical fiber sensors and determine their performance characteristic. So, we looked at all these amplitude, phase, wavelength and polarization modulated sensors. What are the typical issues in making one of those sensors? And how to quantify their performance characteristics? That is, first learning objective.

So, hopefully, you have learned how to do this by now. The second objective is to analyze a given sensing requirement and design an appropriate sensor. So, this is one of the key points as far as this course is concerned. So, you, we looked at some examples where you are asked to do say gas spectroscopy or a bridge monitoring system or distributed acoustic sensing and you are asked to design an appropriate sensor for this.

And we have tried to use some examples to see how this can be done and some of your assignment your tutorial problems were emphasizing this, your final exam is going to be emphasizing this further. So, that is actually one of the things, I hope I have taught you how to do that, I would certainly look forward to understanding or seeing how you are able to do that in your final exam as well.

And the third objective is realize and implement an optimal sensing solution for a given requirement. So, here we are talking about design of the sensor. And here we are talking about implementation of that sensor. Now, this is something that, unfortunately, cannot be done online. But, hopefully you guys can take this forward and look at the implementation phase. Some of you who are keen to do mini projects in this and then through that you understand how this implementation happens.

But that is something that you will keep learning as you start as you keep working in this area further. So, maybe I will end with one quick understanding of how to analyze a given sensing requirement, how to design an appropriate sensor. So, what are the things that you consider when you are picking a sensor?

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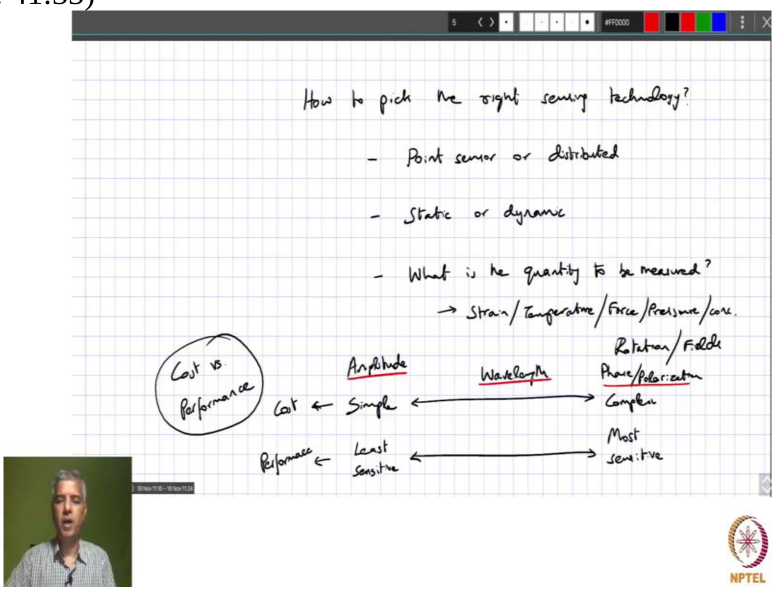

So, how to pick the right sensing technology? So, what do you do first? You look at the requirement and the requirement you ask the question whether it is point sensor or a distributed sensor. So, you can, basically see what that requirement is and of course, your entire sensing configuration is going to change based on whether you need information at only one point or in a distributed manner.

And you also ask the question, whether it is a static or dynamic measurement requirement. So, if it is a static requirement or say it is a quasi-static requirement, like you can make this measurement over several seconds or minutes or even hours, you can take to make that measurement, then you can bring in a lot of this averaging into the picture and then you can try to improve your signal to noise ratio.

But in the case of dynamic, you do not have any opportunity to do averaging type of effects. So, in dynamic cases, you need to do real time processing of your signal. So, sometimes the processing speed at the receiving end is the limitation as far as how fast measurement you can do. But we looked at the case of acoustic emission sensing for example, where we can pick up changes all the way up to megahertz that is that could be achieved using this matched filter technology.

So, it is important to figure out what that requirement is and then look for an appropriate technology and you also want to ask, what is the quantity to be measured? So, when we talk about these quantities to be measured, we can say strain, temperature, some other physical quantities force, pressure, rotation as in the case of gyroscope and fields, electric and magnetic fields.

So, you look at what is the quantity to be measured? And when you look at that you say for example, strain, can you measure strain changes with by looking at changes in amplitude? Yes. So, you step on a fiber that is going to change the amplitude ever so slightly so, if you can pick up that change, yes, you can you can possibly do that. Can you do that with phase? Absolutely. With wavelength? Yes.

Polarization? Yes. So, you could use any one of these, but then the question is the cost to assess performance, this is the primary criteria that you use in determining which one to use. So, for example, if you say rotation, there is hardly anything else that can pick up rotation. So, there you would directly say Sagnac interferometer phase modulated sensor directly. So, there are some very clear cut cases. But there are other cases where multiple technologies multiple avenues can be pursued to achieve this sensing.

Now how do you decide which one is the best for you? Well, so you essentially look at the cost to asses performance criteria. So, if you say from a perspective of cost, you say whether it is going to be simple or as in the case of say, amplitude modulated sensors are typically quite simple to implement.

But on the other hand, if you say, if you want to do this with phase or polarization specifically with all this demodulation mechanism that we have, then that tends to be a bit complex. Because of all the things that we have to do for example of the phase modulator sensor you need to do this phase generated carrier technique and you need to be wary about the coherence of your source.

So, in some cases you need a high coherence source, some cases you need a low coherence source and so on. So, it can be the other end of the spectrum, whereas wavelength modulated sensor is probably somewhere in between, that two. So, that is actually translates to cost, because if it is simpler to implement, then it could be a low-cost sensor. So, we can say that amplitude modulators sensors are typically low-cost sensors whereas this phase or polarization modulated sensors are going to cost you bit more.

Then there is of course, this other issue with performance, where it, where these phase or polarization in approach, where that really scores is in terms of the performance. So, this is actually the most sensitive. So, you even some very small perturbations, strains in the level of nano strains can cause you, cause some significant changes in phase that we can pick up. Whereas, you cannot say the same about amplitude sensors, these are typically least sensitive.

Unless you go for a very special application, like, we are looking at gas concentration. So, we are also looking at concentration of material. So, we are doing some absorption spectroscopy. So there it might be a very special case where it works, but in general for all these other physical parameters, it is not as sensitive. So, this is actually the performance perspective. So, you could, you could have a wide range with respect to this.

And of course, wavelength would be somewhere in between, wavelength actually is like we talked about is very good from the perspective of its robustness with respect to noise. So, that may be very useful for certain application. So, you will have to consider all of this for the given requirement and then come up with your eventual solution.

But hopefully through this course you have learned enough of the tools here, you learned to how to set up a problem and how to analyze for a given requirement and how to design a sensor based on that. So, with that, thank you for your attention as far as this course is concerned and wish you the very best for your future.