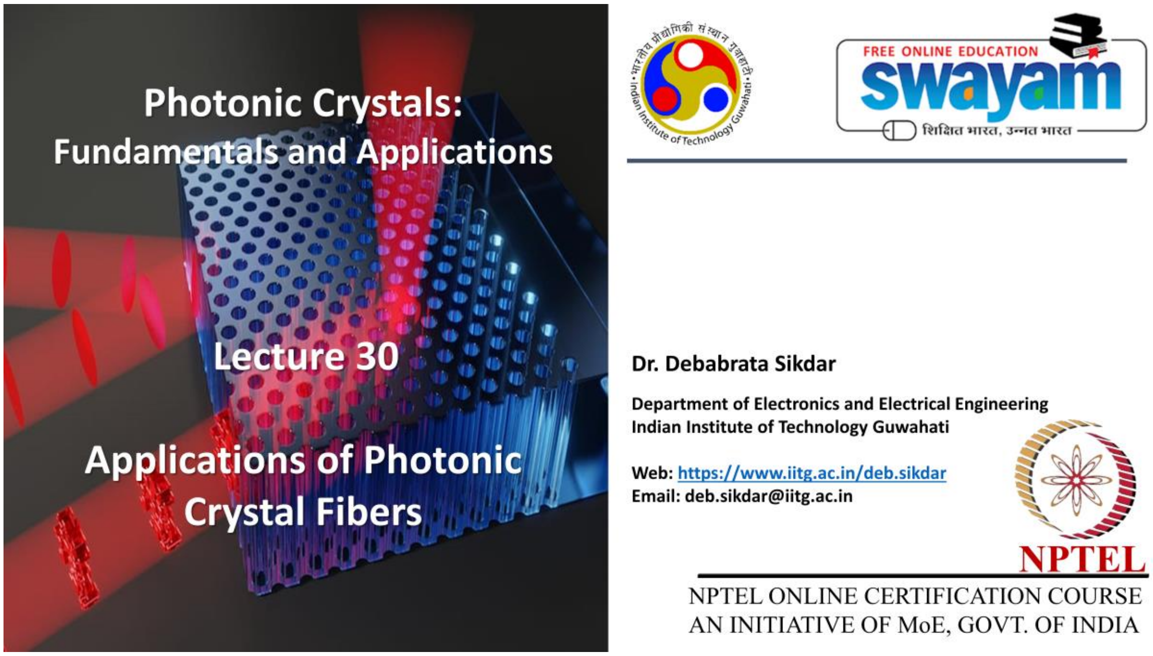
Lec 30: Applications of Photonic Crystal Fibers



Hello students, welcome to lecture 30 of the online course on Photonic Crystals Fundamentals and Applications.

Lecture Outline

- **Photonic Crystal Fibers (PCFs) based Sensors**
  - **Physical Sensors**
    - **Temperature**
    - **Refractive Index**
    - **Electromagnetic field**
  - **Biomedical Sensors**
    - **Glucose**
    - **Blood Components**
- **PCFs for Terahertz Guidance**

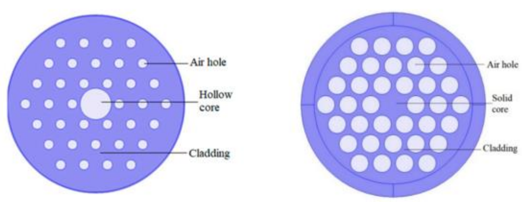
Source: P. Russell, Photonic crystal fibers. science, 299(5605), pp.358-362, 2003.

Today's lecture will be on applications of photonic crystal fibers. So, here is the lecture outline. So, we will discuss about photonic crystal fibers based sensors. We will be discussing about physical sensors for measuring temperature, refractive index, electromagnetic field. We will also discuss about biomedical sensors, measuring glucose and blood components and then we will discuss about PCFs or photonic crystal fibers for terahertz guidance.

Photonic Crystals based Physical Sensors

Photonic Crystal Fibers (PCF) based Physical Sensors

- Photonic Crystal Fibers (PCFs) has an advantageous geometry over standard optical fiber.
- Generally, a PCF has either a hollow core or a solid core around which air holes are distributed in different patterns.



- *Light is guided by the distribution of these air holes.*
- Also, propagation of light can be manipulated by changing the distribution of air holes as well as with the environmental change.

This unique nature of PCF is drawing a lot of attention for its sensing applications.

Source: M. De, T. K. Gangopadhyay, and V. K. Singh, Prospects of photonic crystal fiber as physical sensor: an overview. Sensors, 19(3), p.464, 2019.

So, let us take up the first topic that is photonic crystal- based physical sensors okay. So, photonic crystal fibers have an advantageous geometry over the standard optical fiber okay that is basically this photonic crystal itself right. So, generally a PCF has either a hollow core or a solid core. So, this is a hollow core and then you have air holes okay forming the cladding part or you have a solid core okay with air holes which are distributed in different patterns.

So, light is basically guided by the distribution of these air holes. Also the propagation of light can be manipulated by changing the distribution of the air holes as well as if there is any change with the environment.

Photonic Crystal Fibers (PCF) based Physical Sensors

- PCF-based sensors became the focus of many applications due to their:
  - ✓ High sensitivity
  - ✓ Flexibility
  - ✓ Small size
  - ✓ Robustness
- Therefore, they can be used in many unfavorable situations.
- The small physical dimensions of PCF-based sensing probes make them suitable for attaching or inserting in a system.
- These sensing probes can be connected with the control system without the use of any wire.
- They can be used in a *hazardous and noisy environment or high temperature, high voltage, high electromagnetic field, and explosive environments even for the purpose of remote sensing.*

Source: M. De, T. K. Gangopadhyay, and V. K. Singh, Prospects of photonic crystal fiber as physical sensor: an overview. Sensors, 19(3), p.464, 2019.

So, the unique nature of photon crystal fiber is doing a lot of applications and mainly towards sensing applications. So why they are important? Because photonic crystal fiber based sensors provide high sensitivity, flexibility, small size and robustness. And that's why they can be also used in many unfavorable situations.

The small physical dimension of the photonic crystal fiber based sensing probes make them suitable for attaching or inserting in a system. The sensing probes can be connected with the control system without the use of any wire and they can be used in hazardous and noisy environment or high temperature, high voltage, high electromagnetic field and also even in explosive environments okay even for the purpose of remote sensing.

Photonic Crystal Fibers (PCF) based Physical Sensors

- PCF-based sensors have great design flexibility but also their holey internal structure can be filled with analyte so that a controlled interaction can take place between propagating light and the analyte sample.
- This greatly enhances the sensitivity of fiber optic sensors as well as opens up a new direction for making advanced portable sensors.
- PCF sensors have a wide range of applications for measuring different physical parameters like *temperature, pressure, strain, twist, torsion, curvature, bend, and electromagnetic field* are a few of them.
- Observation as well as control of these parameters are really important in many daily life applications including *civil structural health monitoring*.

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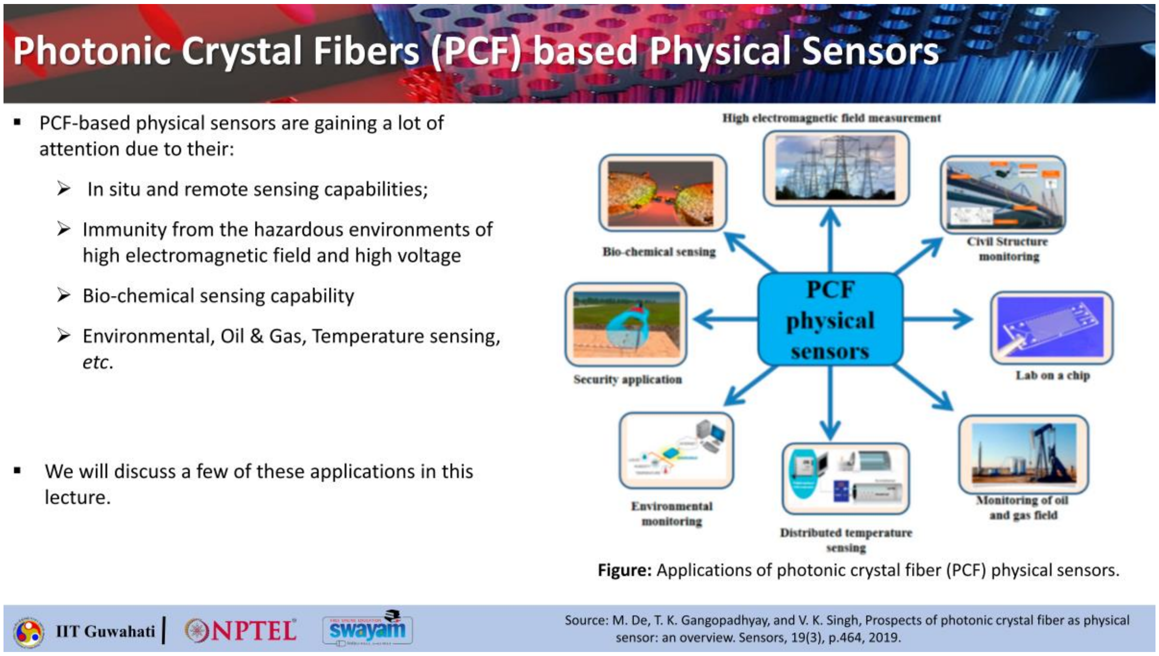
Source: M. De, T. K. Gangopadhyay, and V. K. Singh, Prospects of photonic crystal fiber as physical sensor: an overview. Sensors, 19(3), p.464, 2019.

So, photonic crystal or you can say PCF based sensors have great design flexibility but their wholly internal structure can be filled with the analyte so that you know a controlled interaction can take place between the propagating light and the analyte sample. So this will greatly enhance the sensitivity of the fiber optic sensors and you know they also open up the possibility of making portable sensors. PCF sensors have wide range of applications like measuring different physical parameters such as temperature, pressure, strain, twist, torsion, band, curvature and also electromagnetic field.

So, these are just name a few. So observation as well as control of these parameters are really important in daily applications and one important application is civil structural health monitoring, something like monitoring the health of a dam. and a bridge or some particular wall boundary. As I also mentioned that these are also very useful in border fencing to manage the intrusion detection and safety of a country.



So, PCF or photonic crystal fiber based physical sensors are gaining a lot of attention due to their in-situ and remote sensing capabilities. They have also immunity to hazardous environments of say high electromagnetic fields and also high voltage. So, this kind of sensors will still work within those kind of you know very high field regions and they can be used for biochemical sensing and for oil and gas temperature and so on. So, here is a sorry. So, here is a entire spectrum of different kind of applications. So, as you can see I discussed briefly about security applications in fencing you can use this kind of fibre based sensors, you can use them for biochemical sensing, they can be used for high electromagnetic field measurement, civil structural health monitoring, they can go even smaller like you can use them for lab on a cheap application for monitoring oil and gas fields where it may not be you know easy for other kind of sensors or human being to go and take the data you can be also used for distributed temperature sensing environmental monitoring and so on so we will be basically discussing a few applications in this lecture.

Photonic Crystal Fibers (PCF) based Physical Sensors

Temperature Sensors: Index-Guiding Photonic crystal fiber with liquid ethanol filling

- The material dispersion, in particular, is taken to be the refractive index of the pure silica and the thermo-optic coefficient α of liquid ethanol.

- Thermo-optic coefficient is defined to be:

$$n = n_0 - \alpha(T - T_0)$$

where n and n_0 are the refractive indices at temperature T and T_0 respectively.

- α of liquid ethanol is 3.94×10^{-4}/K.

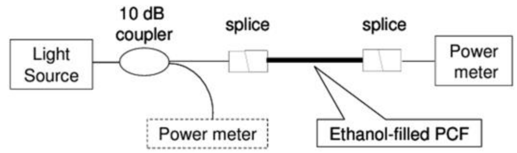


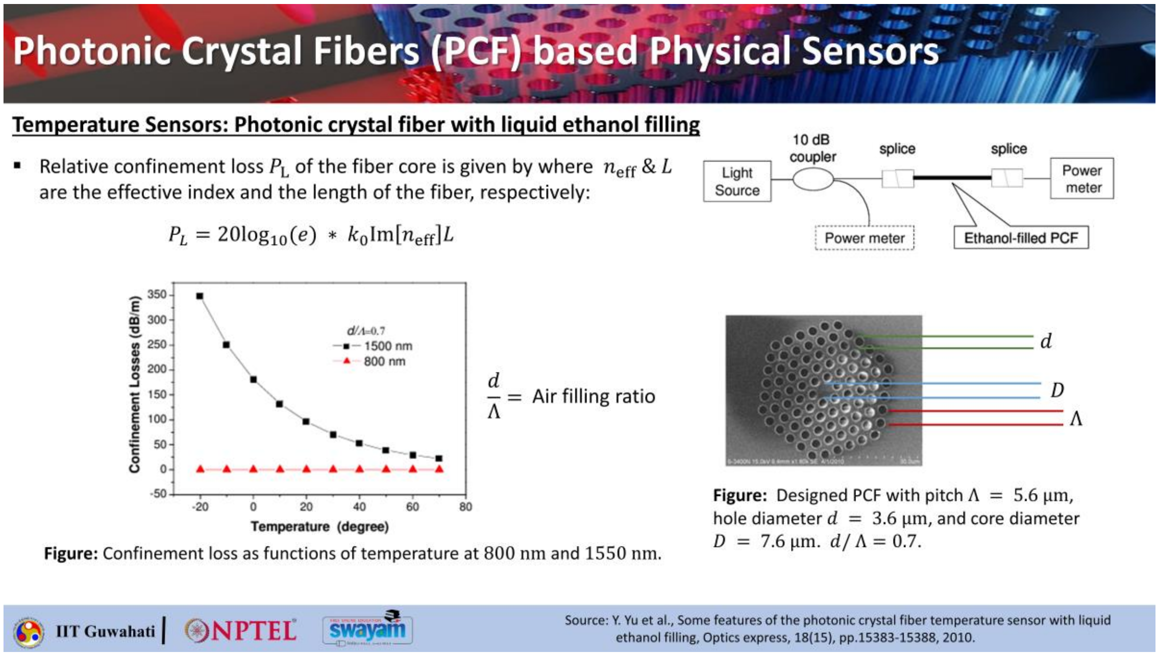
Figure: Experimental setup for temperature sensor.

Source: Y. Yu et al., Some features of the photonic crystal fiber temperature sensor with liquid ethanol filling, Optics express, 18(15), pp.15383-15388, 2010.

So, the first one we will discuss is temperature sensor where we have index guiding photon crystal fiber filled with liquid ethanol.

So, the material dispersion in particular is taken to be pure to be the refractive index of pure silica and the thermo-optic coefficient α of liquid ethanol. So, in that case you know the thermo optic coefficient is defined as $n=n_0-\alpha(T-T_0)$. So, with a change in the temperature it will also affect the refractive index of the material right. So, n and n_0 are basically the refractive index measured at temperature T and T_0 respectively. So, alpha for liquid ethanol is this.

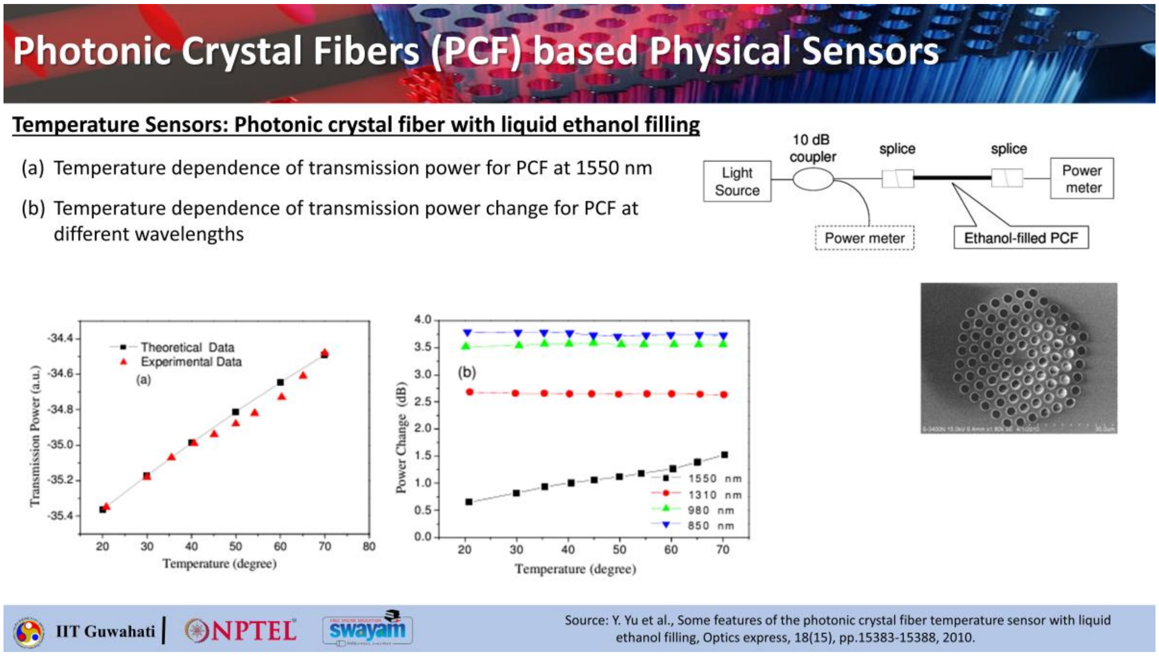
So, this is the you know our thermo-optic coefficient and you can look into the setup in more detail. So, you have a light source and a 10 dB coupler okay. So, you can have a power meter over here okay and then you have this ethanol filled PCF and then also you can measure the power. So, how it works? This is the detailed diagram of this.



So, what will happen? Because the relative confinement loss P_L of the fiber core is given by where n_{eff} & L.

So, P_L is basically given by this formula. So, Okay, so you can see that the relative confinement laws P_L of the fiber core is given by P_L equals $20\log_{10}(e)k_0$ and imaginary power of the effective refractive index times the length of the fiber. So, with this you can actually see that the confinement loss which can be measured as dB per meter and this is how it changes with temperature. And what is d/Λ over here, this is basically the air filling ratio. Now, this can be understood by looking into the fibre cross section.

So, the whole diameter is taken as d okay and the diameter of the core is taken as D and Λ is basically the pitch or the periodicity. So, here are the diameters you can actually see that pitch is 5.6 micron, hole diameter is small d that is 3.6 micron and the core diameter is 7.6 micron. So, if you take small d/Λ ratio that comes out to be 0.7 for this particular fiber. So, here you see that the confinement clause is plotted for two different wavelengths 1500 nanometer the black one and the red triangles for 800 nanometer and it has been a function of temperature. So, you can clearly see that you know at 1500 it shows much more sensitivity. So, this particular figure shows the temperature dependence of transmission power for PCF at 1550 nanometer and the theoretical data and the experimental data more or less coincide and it shows how it can change with you know how the transmission power can change with temperature and that is why you are measuring the power over here ok.



And this particular figure shows you the temperature dependence of the transmission power change. So, this is basically in dB ok and you can see different color actually represents the different wavelength. So, you can clearly see that this particular one which is at 1550 shows much more sensitivity as compared to the other two. So, what we understood here that at 1550 the power received is in direct proportion to the temperature and this is a fact that is consistent with the theory because a lower refractive index of the liquid ethanol is equivalent to an increased temperature. contrast between the core and the cladding indices.

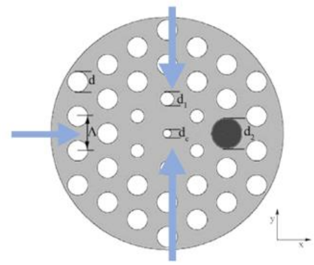
The air leakage to the cladding enhance the confinement loss is reduced with temperature. Finally, owing to the broadening of the propagation modes of the fiber with increasing wavelength The temperature dependence is also more sensitive for the longer wavelength which we can see here. A shorter wavelength it is not much sensitive to the temperature.

Photonic Crystal Fibers (PCF) based Physical Sensors

Refractive Index Sensors

- Refractive index is an important basic physical parameter.
- In situ measurement of it helps to identify a material in many practical fields, like, *chemical industry, gas and oil field industry, food processing and quality control industry, to check the adulteration level in liquid, for the identification of biomolecules*, etc.

- The three layers of cladding air holes (in silica) are arranged in a triangular lattice.
- The lattice pitch is $\Lambda = 4$ μm.
- Central air hole is $d_c = 1$ μm, which helps reduce the effective index of the fundamental mode, making it easier to match between the core mode and the defect mode.
- The cladding air holes of the first layer have a diameter of $d_1 = 1.6$ μm and function similar to the central air holes, which adjusts the sensitivity of the sensor by adjusting the overlap of the evanescent field and the analyte.



Source: Y. Wang et al., High-sensitivity photonic crystal fiber refractive index sensor based on directional coupler, Optical Fiber Technology, 49, pp.16-21, 2019.

Now we move on to the next type that is refractive index sensor. So, refractive index is an important basic physical parameter as we all know.

In-situ measurement of this parameter will help to identify a material in many practical application such as in chemical industry, gas and oil field, food processing, quality control and that will basically help us to check any kind of adulteration in liquid or it can also help us in identifying biomolecules. So, to do that basically this kind of a PCF is involved. So, here the three layers of the cladding air holes in silica are. So, you can see these are three layers basically of the cladding air holes. So, basic is the background silica fiber and they are all arranged in a triangular array and you can see the lattice pitch here is 4 micron.

The central hole diameter is a very small one. It is only it is given as d_c central hole and it is 1 micron and this helps reduce the effective index of the fundamental mode making it easier to match with the core mode and the defect mode. And then you have cladding air holes okay this one and this one okay. So, also this okay this is the first layer one okay and the cladding holes of the first layer has got the diameter d_1 equals 1.6 micron and they would function similar to the central air holes which adjust the sensitivity of the sensor by adjusting the overlap of the evanescent field with the analyte.

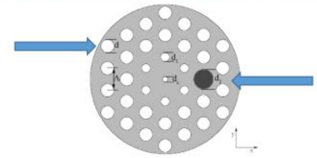
Photonic Crystal Fibers (PCF) based Physical Sensors

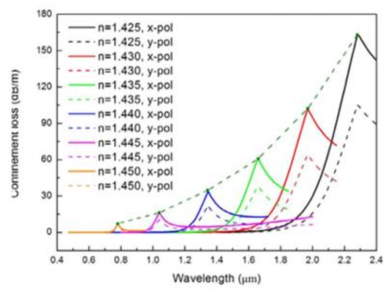
Refractive Index Sensors

- The diameter of the black air hole filled with the analyte is $d_2 = 3.6$ μm.
- The diameter of the other air holes is $d = 2.4$ μm.
- Refractive Index of the analyte is represented by n.
- The confinement loss of the modal can be calculated as:

$$P_L = 20\log_{10}(e) * \ k_0 \mathrm{Im}[n_{\mathrm{eff}}] L$$

- Confinement loss spectra of core mode as a function of wavelength with the analyte refractive index changing from 1.425 to 1.450:





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Source: M. De, T. K. Gangopadhyay, and V. K. Singh, Prospects of photonic crystal fiber as physical sensor: an overview. Sensors, 19(3), p.464, 2019.

So, what is the role of the second one? The dark air filled or you can say the diameter. The diameter of the black air hole filled with the analyte is considered to be d_2 and that is 3.6 micron. and the remaining air holes are all having a diameter of 2.4 micron and that is represented by d.

So, the refractive index of the analyte which is getting measured is represented by n. So, here also you can find out the confinement loss of the mode or you can say modal loss can be calculated as $P_L = 20\log_{10}(e) k_0 \mathrm{Im}[n_{\mathrm{eff}}] L$. okay and the confinement loss spectra for the core mode as a function of wavelength with the analyte different refractive indices are shown over here. So, you can see this is the loss and this is the wavelength and this is what is happening for different refractive index of the analyte.

Photonic Crystal Fibers (PCF) based Physical Sensors

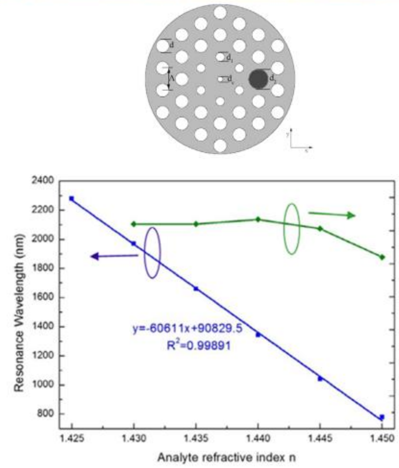
Refractive Index Sensors

- The RI is the main factor affecting the RI sensing mechanism.
- The sensitivity of the proposed sensor can be expressed as:

$$S = \frac{\Delta\lambda_{\text{peak}}}{\Delta n}$$

where $\Delta\lambda_{\text{peak}}$ and Δn represent the amount of change in the resonance wavelength and the analyte RI.

- The detection limit of the sensor is the minimum change in the RI detectable by the sensor. $\Delta\lambda_{\min}$ is the minimum spectral resolution.
- The smaller the detection limit, the better the performance of the sensor. It can be written as: $R = \Delta n \Delta\lambda_{\min}/\Delta\lambda_{\text{peak}}$



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Source: M. De, T. K. Gangopadhyay, and V. K. Singh, Prospects of photonic crystal fiber as physical sensor: an overview. Sensors, 19(3), p.464, 2019.

So, the refractive index is the main factor that basically affects the refractive index sensing mechanism. So, the sensitivity of the proposed sensor can be expressed as $(\Delta\lambda_{\text{peak}})/\Delta n$. So for unit change in refractive index, how much is basically the shift in the wavelength right, wavelength peak or you can say peak wavelength change. So, these two can be measured and you can find out the sensitivity. So, the detection limit of the sensor is the minimum range in the or minimum change in the refractive index which is detectable by this sensor and $\Delta\lambda$_min shows the minimum spectral resolution. So, the smaller the detection limit, the better will be the performance of the sensor.

So, you can write you know $R=\Delta n\Delta\lambda_{\min}/\Delta\lambda_{\text{peak}}$. So, this one shows the resonance wavelength is a function of the analyte refractive index and you can see it is a pretty much linear plot ok and this is the plot of the sensitivity. So, you can also see the sensitivity is represented by nanometer per RIU that is the refractive index unit and you can see this is a very very sensitive very very high sensitive sensors ok. So, if you assume $\Delta\lambda_{\min}$ to be 0.1 you can calculate the refractive index of the analyte in the range of say 1.425 to 1.5 and 1.45 to 1.6 the corresponding minimum detection limit will be something like 1.6 into 10 to the power minus 6. refractive index unit something like that. So, it is a very very you know sensitive sensors.

Photonic Crystal Fibers (PCF) based Physical Sensors

Electromagnetic Sensors

- Electromagnetic field and associated force is one of the fundamental forces of nature.
- It creates strong and detectable for high electricity consuming objects which is harmful for leaving beings but this field is not detectable by the sense organs.
- So sensing of this field as well as its current in many cases is an important task.
- In electric power industry and other places presence of metal may influence the electromagnetic field measurement.
- So, fiber optics sensors are suitable for the same.
- Also, the properties of fiber for remote sensing are small size, non-conducting nature, and immunity to electromagnetic interference representing them as a suitable candidate in making electromagnetic sensors based on PCF.

Source: M. De, T. K. Gangopadhyay, and V. K. Singh, Prospects of photonic crystal fiber as physical sensor: an overview. Sensors, 19(3), p.464, 2019.

So, the next one is electromagnetic sensor.

So, electromagnetic field and the associated force is also one of the important and fundamental force of nature. It basically creates strong and detectable for high electricity consuming consuming objects which is harmful for. So, the next one is electromagnetic sensors. So, electromagnetic field and associated force is one of the fundamental forces of nature. It creates strong and detectable pattern for high electricity consuming objects which is harmful for living beings.

But this field is not detectable by sense organs. So sensing this field as well as its current in many cases is an important task. So, in electric power industry and other places presence of metal may influence the electromagnetic field measurement. So, the fibre optic sensors become very suitable for this kind of applications. Also, the properties of fiber for remote sensing are small size, they are non-conducting in nature and they have immunity to electromagnetic interference and that all these things make them suitable candidate for making electromagnetic sensors based on PCF.

Photonic Crystal Fibers (PCF) based Physical Sensors

Electromagnetic Sensors

- Infiltration of liquid crystal (LC) materials into the microholes of the PCF has been extensively studied for various in-fiber tunable device applications.
- Infiltration of LC materials makes the PCF susceptible to external field variations, a property which can be utilized to fabricate all-fiber sensors for parameters such as temperature, magnetic fields, and electric fields.
- Solid silica core PCFs usually transmit light through a modified total internal reflection (m-TIR) mechanism.
- Infiltration of high-index materials ($> n_{\text{silica}}$) such as LCs causes the transmission mechanism to change from modified TIR to photonic bandgap guidance.
- On infiltration the holey cladding region of the PCF assumes the effective refractive index of the infiltrated LC material, which is usually higher than that of the silica core region.
- Under these conditions the guiding properties of the PCF are primarily governed by the antiresonant reflection from multiple cladding layers, and the transmission spectrum of the structure is determined by the refractive index contrast of the cladding layers.

Source: S. Mathews, G. Farrell, and Y. Semenova, Liquid crystal infiltrated photonic crystal fibers for electric field intensity measurements, Applied Optics, 50(17), pp.2628-2635, 2011.

So, inflation of liquid crystal materials into these micro holes of the photonic crystal fibres has been extensively studied for various types of in fibre tunable device applications. infiltration of liquid crystals materials will make this photonic crystal fibers susceptible to the external field variation. And a property which can be utilized to fabricate all fiber sensors for parameters like you know temperature, magnetic field and electric field. Solid core PCFs they usually transmit light. through a modified total internal reflection mechanism which we have already discussed.

And if you have infiltration of high index material which are basically larger than silica such as the liquid crystals, they can cause the transmission mechanism to change from modified total internal reflection to you know the photonic bandgap guidance. So, the mechanism of light propagation itself can change when you introduce this you know infiltration of liquid crystal in photonic crystal fiber. So, on infiltration the holey cladding region of the PCFs would assume the effective refractive index of the infiltrated liquid crystal material which is usually higher than that of the silica core region. So, under this you know conditions, the guiding properties of the PCFs are primarily governed by the anti-resonant reflection from multiple cladding layers and the transmission spectrum of the structure will then be determined by the refractive index contrast of the cladding layers.

Photonic Crystal Fibers (PCF) based Physical Sensors

Electromagnetic Sensors

- Liquid Crystal (LC): filling in a PCF as a sensor probe was reported for measuring high electric field intensity with sensitivity ~10.1 dB/kV rms/mm for the electric field intensity range 2.35– 4.95 kV rms/mm and resolution ~1 V rms/mm.

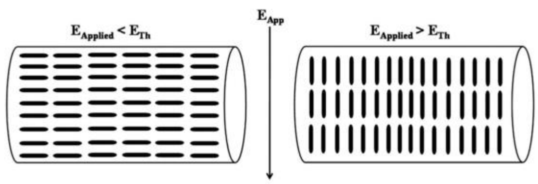

Figure: Orientation of LC molecules within PCF holes below and above the threshold field.

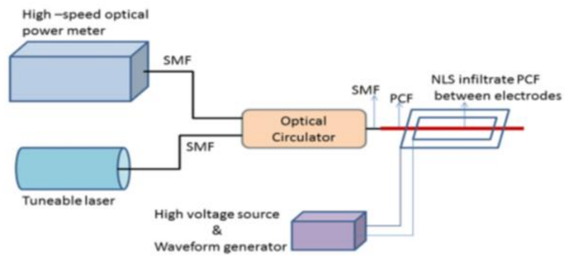

Figure: Schematic of the experimental setup to study reflected power response of the liquid crystal infiltrated PCF probe for the measurement of external electric field intensity.

Source: S. Mathews, G. Farrell, and Y. Semenova, Liquid crystal infiltrated photonic crystal fibers for electric field intensity measurements, Applied Optics, 50(17), pp.2628-2635, 2011.

Photonic Crystal Fibers (PCF) based Physical Sensors

Electromagnetic Sensors

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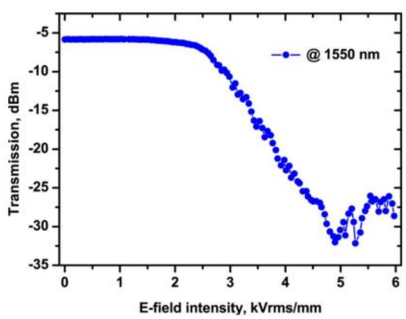


Figure: Response of sensor with a changing electric field intensity (1 kHz) at 1550 nm measured at room temperature.

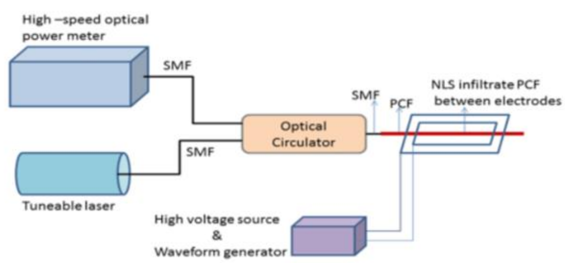


Figure: Schematic of the experimental setup to study of the liquid crystal infiltrated PCF probe for the measurement of external electric field intensity.

Source: S. Mathews, G. Farrell, and Y. Semenova, Liquid crystal infiltrated photonic crystal fibers for electric field intensity measurements, Applied Optics, 50(17), pp.2628-2635, 2011.

So, electromagnetic sensors, so if you see this particular figure, it shows you the schematic of the experimental setup to study reflected power response of the liquid crystal infiltrated PCF probe for the measurement of external electric field intensity.

So what is done here? So you have this liquid crystal filling in a photonic crystal fiber and it is used as a sensor probe and for measuring high electric field intensity with sensitivity of the order of 10 to the power 10.1 dB per kilo volt okay rms per mm okay. For the electric field intensity ranges from this and it gives you a resolution of 1 volt rms per mm. So, what you have here is high speed optical power meter, there is a single mode fiber cable and then you have a tunable laser, you have optical circulator and this is the single mode fiber to which this PCF probe is connected and this is where you know there are electrodes. between which this liquid crystal infiltrate PCF is placed.

And then these electrodes are basically connected to high voltage source and waveform generator. So, what happens you can see from this schematic that the orientation of the liquid crystal molecules within the PCF holes below and above the threshold field. So, if you apply electric field below the threshold field they are all aligned like this, but as soon as you make the field stronger than the threshold they all align with the particular field ok. So, using this method you can measure you know the transmission through this particular sensor. So, you can say the response of the sensor with a changing electric field intensity and the frequency is of 1 kilohertz okay at 1550 nanometer that is measured at room temperature right and you can see that the transmission at different electric field intensity behaves in this kind of a pattern.

Photonic Crystals based Biomedical Sensors

Photonic Crystal Fibers (PCF) based Biomedical Sensors

- In terms of biomedical uses, PCFs can determine:
  - ✓ Glucose concentrations
  - ✓ Detecting different types of blood components
  - ✓ Identifying a blood cancer
  - ✓ Calculating the proteins
  - ✓ DNAs
  - ✓ Distinguish between pathogenic and hereditary diseases

By injecting samples into a photonic crystal waveguides which displays infection levels and/or sensitivity.

Let us discuss a few of these applications in this lecture.

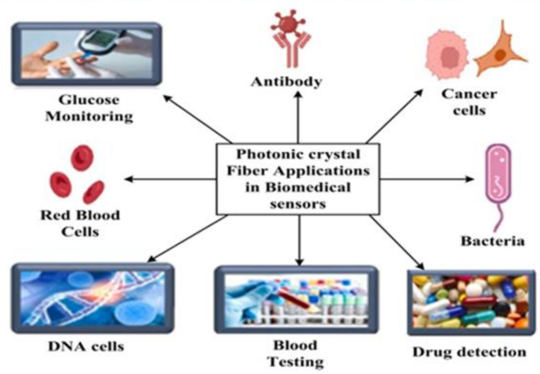
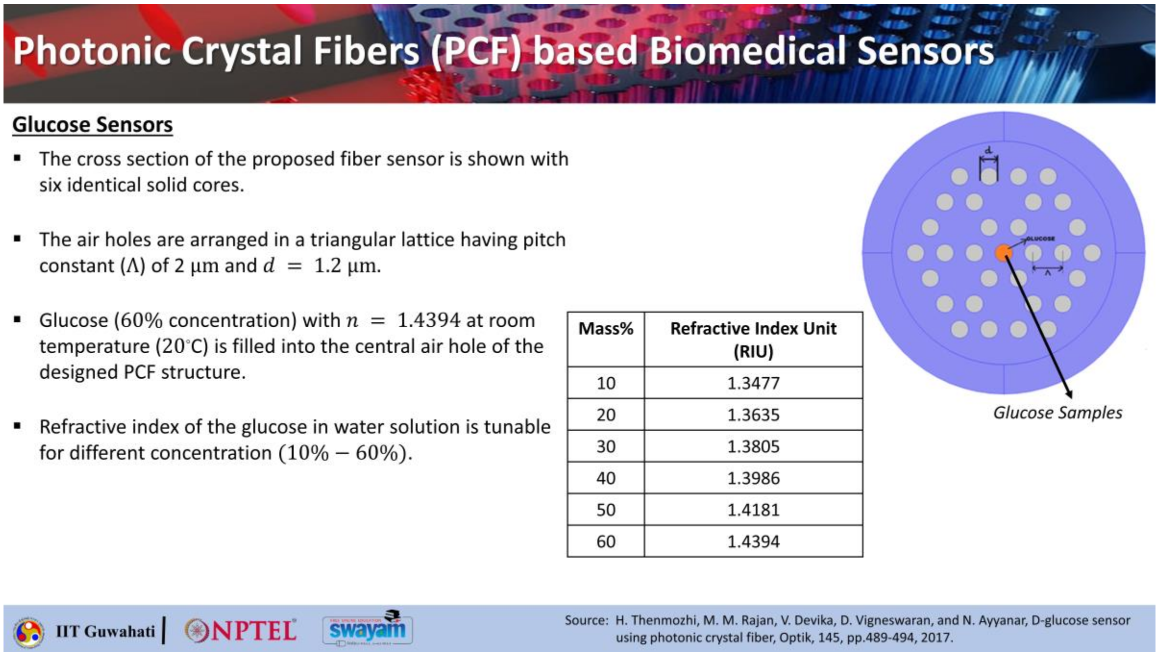


Figure: Schematic representation of photonic crystal fiber uses in biomedical sensors.

Source: M. De, T.K. Gangopadhyay, and V. K. Singh, Prospects of photonic crystal fiber as physical sensor: an overview. Sensors, 19(3), p.464, 2019.

So, you can also use photonic crystals for biomedical sensors. So, in terms of biomedical usage, PCFs can determine the following. So, you can think of you know glucose concentration measurement, detecting different types of blood components, identifying a blood cancer, calculating the proteins, DNAs, distinguish between pathogenic and hereditary diseases. okay and by so these are all done by injecting the samples into a photonic crystal so that there is a typo over here okay never mind. So by injecting samples into photonic crystal waveguides which displays infection level or sensitivity.

we will take some of these applications as you can see here. These are graphically presented or schematically you can say. So, you can use the photonic crystal fiber for drug detection, blood testing, counting red blood cells, DNA cells, then glucose monitoring, cancer cell detection, and so on.



Mass%	Refractive Index Unit (RIU)
10	1.3477
20	1.3635
30	1.3805
40	1.3986
50	1.4181
60	1.4394

So let us take one commonly used sensor, which is a glucose sensor. So this is the cross-section of the proposed fiber sensor, which is shown with six identical solid cores.

And the air holes are basically arranged in a triangular lattice having pitch constant of 2 microns and the diameter d of 1.2 micron. So, the glucose concentration if you take like 60 percent ok, which has got a refractive index of 1.4394 at room temperature. So, we are considering 20 degrees at the room temperature here and that is filled in the central hole of the design PCF.

So, this is how you know the refractive index of the glucose in water will change with different concentrations. So, if you change the percentage from 10 percent to 60 percent this is how the refractive index will change.

Photonic Crystal Fibers (PCF) based Biomedical Sensors

Glucose Sensors

- The confinement loss can be calculated as:

$$\alpha = 8.686 \times \frac{2\pi}{\lambda} \mathrm{Im}(n_{\mathrm{eff}}) \times 10^{6}\ \mathrm{dB/m}$$

- $\mathrm{Im}(n_{\mathrm{eff}})$ represents the imaginary part of the effective refractive index of mode.

- The spectral sensitivity of the corresponding sensor can be obtained as:

$$S = \frac{\Delta\lambda_{\mathrm{peak}}}{\Delta n}$$

where $\Delta\lambda_{\mathrm{peak}}$ and Δn represent the amount of change in the resonance wavelength and the analyte RI.

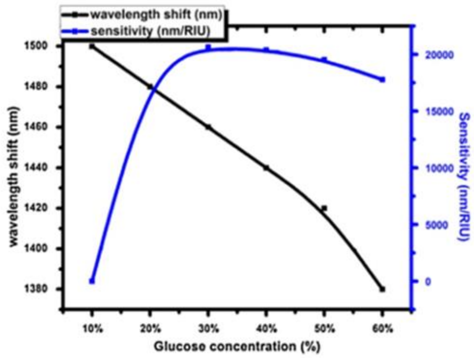


Figure: Resonance wavelength as the function of varying glucose concentration.

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Source: H. Thenmozhi, M. M. Rajan, V. Devika, D. Vigneswaran, and N. Ayyanar, D-glucose sensor using photonic crystal fiber, Optik, 145, pp.489-494, 2017.

So, the unit used here is refractive index unit ok. Usually there is no unit at that, but this is where it is important to you use this unit for calculation of sensitivity and so on. So, with increase in the concentration the refractive index increases ok.

So, this is how the confinement loss can again be calculated. So, this same 20 log 10(e). So, you can actually get the numerical value from here.

It is $8.686 \times 2\pi/\lambda\ \mathrm{Im}(n_{\mathrm{eff}}) \times (10)^{6}$ dB/m. So, as I mentioned, so imaginary of n_{eff} basically represents the imaginary part of the effective refractive index of a particular mode right. So, the spectral sensitivity of the corresponding sensor is obtained. So, here different colors correspond to the different concentration and you can see that their peak wavelengths are also different and these are the y axis tells you about the loss which is dB per meter. So, this is a relationship with relationship between the confinement loss and the different samples of glucose solution right. So, if you try to plot the you know spectral sensitivity of this particular sensor you can say S equals $(\Delta\lambda_{\mathrm{peak}})/\Delta n$.

So, what is $\Delta\lambda_{\mathrm{peak}}$ that is the change in the peak wavelength and delta divided by Δn sorry. So, Δn is basically the amount of change in the refractive index ok. So, that will give you you know. So, here the black line as the color coding here shows this gives you the wavelength shift ok in nanometer with different glucose concentration and this is the sensitivity that has been calculated ok.

Photonic Crystal Fibers (PCF) based Biomedical Sensors

Blood Components Sensors

- Refractive indices of body fluid components:

Component	Refractive index
Water	1.33
Plasma	1.35
WBC	1.36
Hemoglobin	1.38
RBC	1.40
Water	1.33

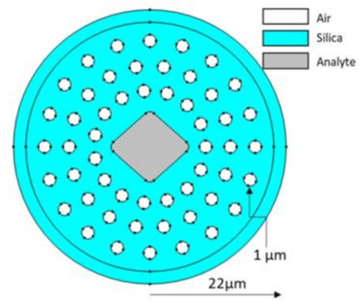

Figure: Proposed photonic sensor design.

- Refractive indices of silica is calculated using the Sellmeier equation:

$$n_{\text{silica}} = \sqrt{1 + \frac{0.696166\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\lambda^2}{\lambda^2 - 9.896161^2}}$$

Here, λ represents the operating wavelength.

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Source: H. Akhdar *et al.*, Blood component detection using photonic crystal fibre sensor. Optical and Quantum Electronics, 56(1), p.75, 2024.

The next one is. blood component sensor. So, for that you can you have to first know what are the refractive indices of different body fluid components. So, if you take water it has got a refractive index of 1.33, plasma has blood plasma has 1.35, WBC has 1.36, hemoglobin has 1.38, RBC has got 1.40 ok. So this is the proposed photonic sensors where these are the air holes, the background is silica and this is the core where the analyte will be placed and the silica can be represented by the refractive index given by this Sellmeier equation. So, how do you detect the different components?

Photonic Crystal Fibers (PCF) based Biomedical Sensors

Blood Components Sensors

- Confinement loss : $\alpha = 8.686 \times \frac{2\pi}{\lambda} \mathrm{Im}(n_{\mathrm{eff}}) \times 10^6 \ \mathrm{dB/m}$

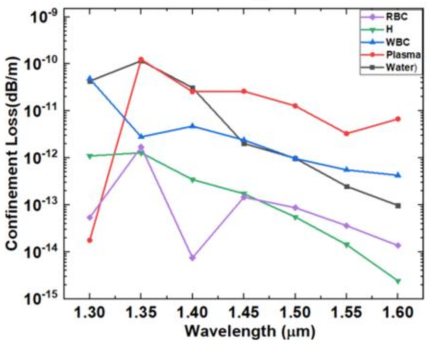


Figure: Confinement Loss with wavelength for different samples.

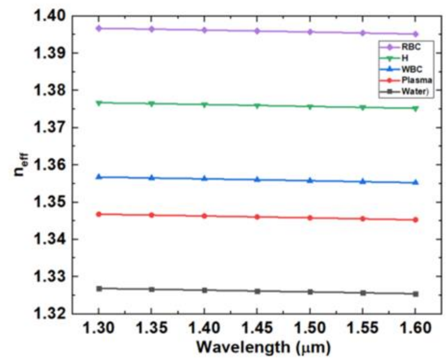


Figure: Effective refractive index (n_{eff}) with wavelength for the proposed sensor.

Source: H. Akhdar *et al.*, Blood component detection using photonic crystal fibre sensor. Optical and Quantum Electronics, 56(1), p.75, 2024.

Again, you can measure what is the confinement loss, same equation can be used. And you can see that these are the confinement laws with wavelength for different samples. So, RBC, WBC, plasma, water, all of them have different values. Similarly, you can also understand that they will show different effective refractive index.

for this. So, different components of the blood will have different effective index that also you can see from this particular figure. So, that helps you to detect different components in the plant.

Photonic Crystals Fibers for Terahertz Guidance

Photonic Crystals Fibers for Terahertz Guidance

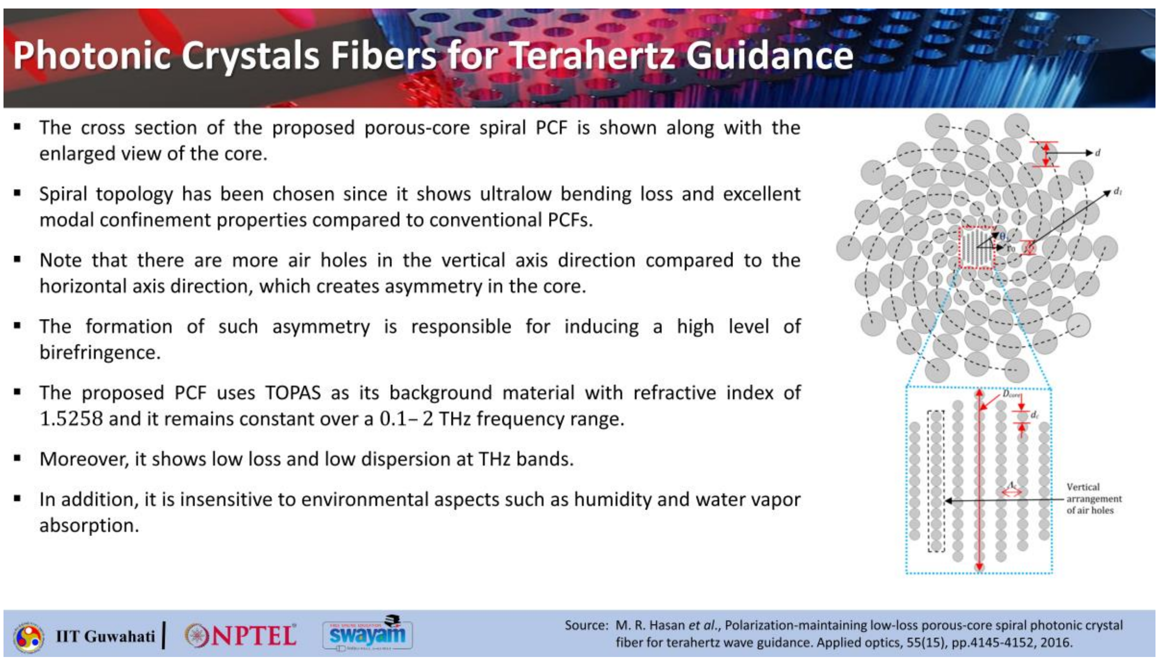
- It is known that dry air is the most transparent medium for THz propagation since it does not absorb THz waves.
- Under this supposition, an array of smaller air holes also known as subwavelength porous air holes is placed in the solid material core of a photonic crystal fiber (PCF).
- *Thus, by transmitting most of the mode power through the porous air core, it is possible to propagate THz waves with minimum absorption losses.*
- One of the most important properties showed by porous core PCFs is the controllability of birefringence.
- Birefringence is induced in polarization-maintaining PCFs by deliberately breaking the symmetry of either core or cladding.
- A porous-core spiral PCF will be discussed in order to achieve ultrahigh birefringence by intentionally creating asymmetry in the core.
- Other important modal properties such as effective material loss, bending loss, power fraction, dispersion, and confinement loss are thoroughly discussed with the variation of different structural parameters.

Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

So, the last topic will be on photonic crystal fibers for terahertz guidance. So, it is known that dry air is the most transparent medium for terahertz propagation since it does not absorb terahertz waves. So, under this concept an array of smaller air holes also known as subweb length porous air holes is basically placed in the solid material core of a photonic crystal fiber.

So, thus by transmitting more most of the more power through the porous air core it is possible to propagate terahertz waves with minimum absorption loss. So, that is the whole idea because terahertz has got lowest loss in the dry air. So, one of the most important properties showed by the porous core PCFs is the controllability of birefringence. Now, birefringence is basically induced in polarization maintaining PCFs by deliberately making the symmetry of either you know by deliberately breaking the symmetry of either core or cladding. So, a porous core spiral PCF will be shown in this lecture that will help you to achieve ultra high birefringence by intentionally creating asymmetry in the core.

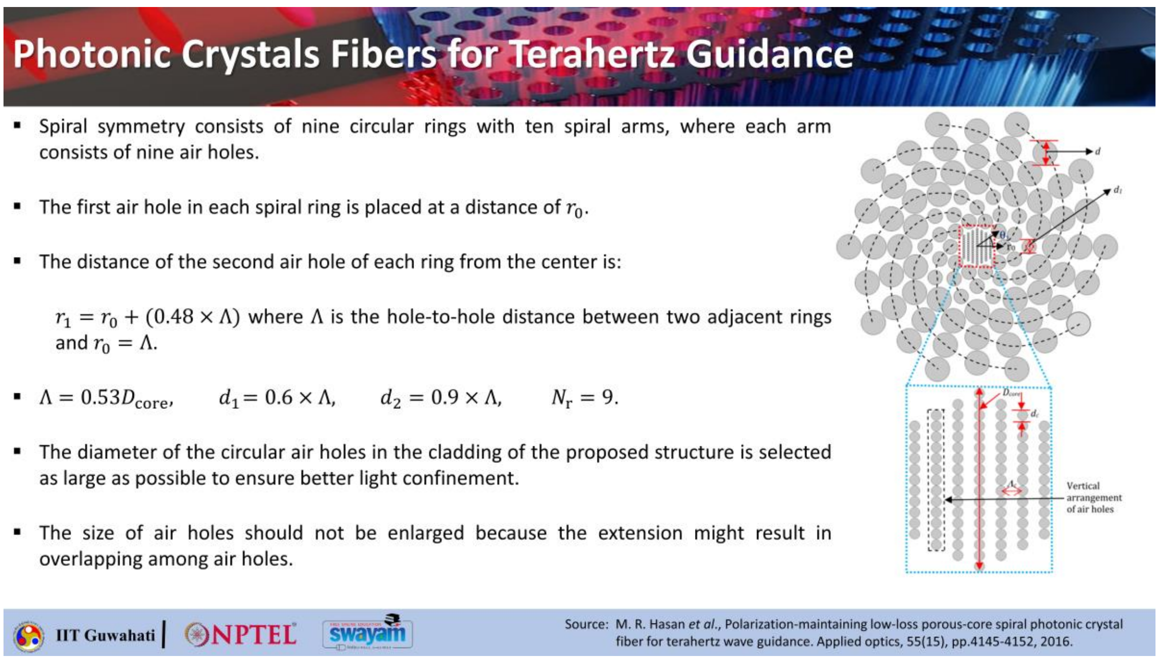
Other important model properties such as effective material loss, bending loss, power fraction, dispersion and confinement loss, these will be thoroughly discussed by considering the variation of different structural parameters.



So, this is a very unique design of porous core spiral photonic crystal fiber that was reported in this particular research paper, okay. So, you can see that the core is now shown in a very enlarged view. So, these are vertical arrangement of air holes, these are all air holes but of different radius and they are placed along a different spirals. So, the spiral topology has been chosen since it allows ultralow bending loss and It offers excellent mode confinement properties as compared to the conventional PCFs.

So note that there are more air holes in the vertical axis direction compared to the horizontal axis direction and this creates asymmetry in the core. and the formation of such asymmetry is responsible for inducing a high level of birefringence. Birefringence means there are different refractive index along the two different direction. So, that way you know the proposed PCF uses topaz as its background material which is a refractive index of 1.

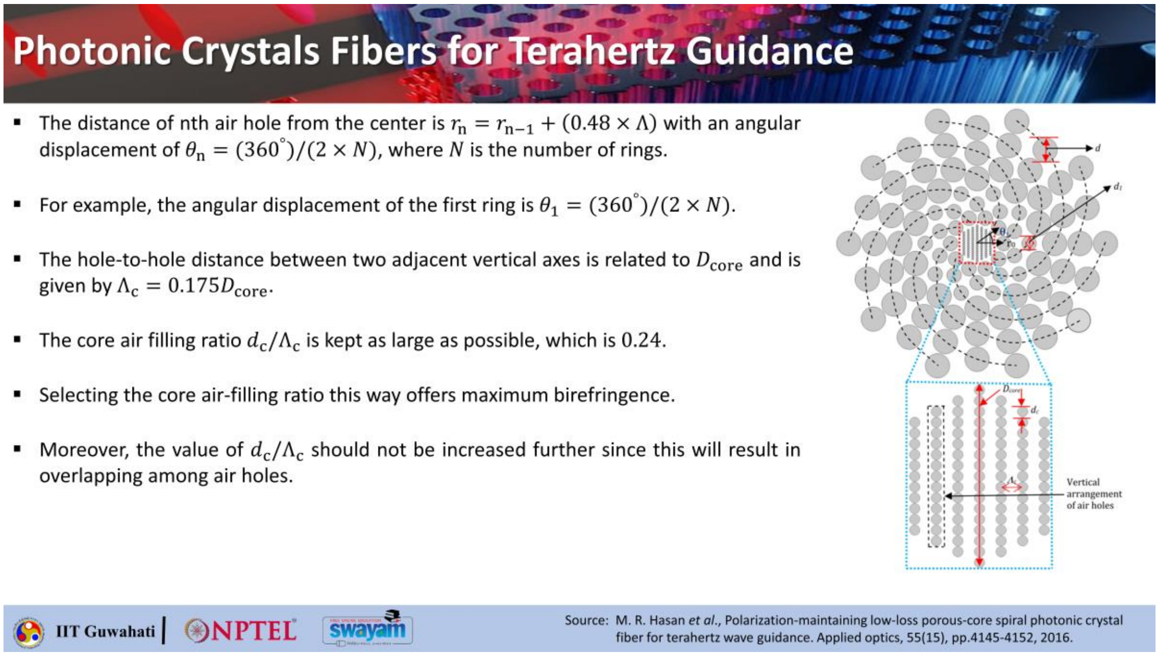
5258 and it remains constant over the frequency range of 0.1 to 2 terahertz. Moreover, it shows low loss and low dispersion at terahertz bands. In addition, it is insensitive to environmental aspects such as humidity and water vapor absorption.



Spiral symmetry consists of 9 circular rings and 10 spiral arms where each arm consists of 9 air holes. So, the first air hole in each spiral ring is placed at a distance of r_o as shown here.

And the distance of the second air hole of each ring from the center is calculated as r_1, which is $r_0+(0.48\times\Lambda)$. That is Λ, which is the hole-to-hole distance between the two adjacent rings. And you can take r_0 equals Λ.

So these are the parameters considered over here. and the diameter of the circular air holes in the cladding of the proposed structure is selected as large as possible and that will ensure better light confinement. The size of the air holes should not be enlarged because the extension might result in overlapping of some of the air holes.

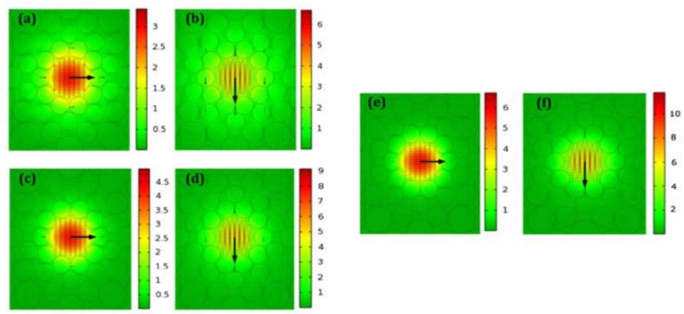


Yeah, that is very important. So, the number of air hole rings is selected as maximum. Here, n_r okay that is n_r is taken as 9. So, this is the maximum possible to obtain low confinement loss since increasing the number of rings in the outer cladding results in tight light confinement in the core. So the distance of the nth air hole from the center can be calculated using this iterative formula and it can also shows an angular displacement of θ_n which is given by =$(360°)/(2×N)$ where N is basically the number of rings. For example, here you can calculate the angular dispersion of the first ring to be θ_1 that is 360 divided by 2N. The hole to hole distance between adjacent vertical axis is related to D_{core}.

So, this is D_{core} and this is D_c, this is Λ_c. So, here you can see that Λ_c is basically 0.175 of D_{core}. So, the core air core filling ratio that is d_c/Λ_c is kept as large as possible which is here 0.24. So, selecting the core air core filling ratio this way will offer maximum birefringence.

Moreover, the value of d_c/Λ_c should not be increased further since this will result in overlapping of few of these holes. So, that is the maximum limit.

Photonic Crystals Fibers for Terahertz Guidance



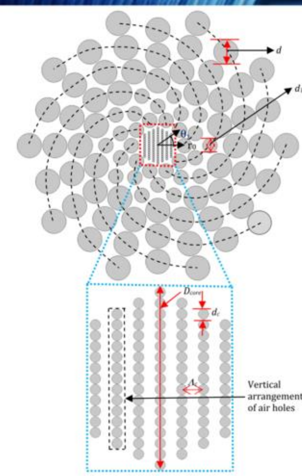


Figure: Mode field distributions of the proposed PCF for $D_{\text{core}} = 410$ µm and different operating frequencies of (a) 0.8 THz x-polarization, (b) 0.8 THz y-polarization, (c) 1 THz x-polarization, (d) 1 THz y-polarization, (e) 1.2 THz x-polarization, and (f) 1.2 THz y-polarization.

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Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

So, if you want to go into more details of why this design was initiated and what are the minute details of the design, you can always refer to this paper that is shown in the reference. So, here we show the mode field distributions of the proposed PCF for D_{core} equals 410 microns and different operating frequencies.

So, this a is for 0.8 terahertz X polarization and the B is for Y polarization and this one is for 1 terahertz X polarization and this is 1 terahertz Y polarization. This is for 1.2 terahertz X polarization and this one is for 1.2 terahertz Y polarization right. So, to operate as an effective polarization-maintaining terahertz PCF, the level of the birefringence should be as high as possible.

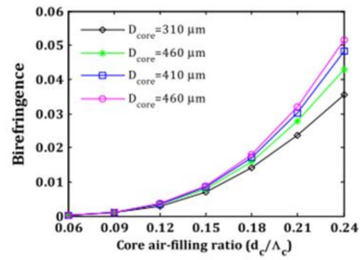
So, one important thing here is that you know this mode distribution shows strong confinement of modes in the core, isn't it?

Photonic Crystals Fibers for Terahertz Guidance

- To operate as an effective polarization-maintaining THz PCF, the level of birefringence should be as high as possible.
- The birefringence has been calculated using the following formula:

$$B = |n_x - n_y|$$

- B stands for birefringence, n_x and n_y are the effective refractive indices of the x-polarization and y-polarization modes, respectively.
- Birefringence as a function of the core air-filling ratio d_c/Λ_c for different D_{core} at $f = 1$ THz.
- As seen in the figure, birefringence is an increasing function with increasing d_c/Λ_c for the same value of D_{core}.



Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

So the birefringence as we are talking about so the birefringence should be as high as possible. So birefringence can be written as $|n_x - n_y|$. So B is basically birefringence n_x and n_y are the refractive index or you can say effective refractive index along x and y direction or they are also associated with the x polarization and the y polarization modes. So the birefringence as a function of air core filling factor that is d_c/Λ_c at frequency of 1 terahertz is plotted here. As you can see that the birefringence keep on increasing with increasing this ratio for the same value of D_{core}.

So, these are the different core diameters which are considered. So, the reason can be understood due to the fact that when d_c/Λ_c is increased the diameter of the porous air holes also increases. Therefore, induced asymmetry becomes stronger and as a result your birefringence will increase. Obviously, this structure exhibits nearly zero birefringence without porous air holes. It is important to note that the maximum value of birefringence d_c/Λ_c is said to be equal to or less than 0.2 for here ok. Because further extending the value of d_c/Λ_c will result in overlap of the air holes along the vertical axis that we have discussed previously right. So, when the D_{core} is increased the air holes actually become larger. That is true. So, therefore, asymmetry between the X polarization and Y polarization mode enhances and thus your birefringence also increases.

An ultra-high birefringence of 0.0483, okay, that is a very high value for birefringence that can be achieved at 1 terahertz frequency if we choose D_{core} to be 410 micron and d by d_c/Λ_c to be 0. D_{core} equal to you know 0.24 right. So, this is the value we are reporting ok.

Photonic Crystals Fibers for Terahertz Guidance

- Effective material loss (EML) is an important parameter in designing PCFs used for THz guidance and is quantified by the following expression:

$$\alpha_{\text{eff}} = \frac{(\varepsilon_0/\mu_0)^{1/2}\int_{A_{\text{mat}}} n\alpha_{\text{mat}}|E|^2 dA}{2\int_{\text{All}} S_z dA}\,\text{cm}^{-1}$$

where ε_0 and μ_0 are the permittivity and permeability of vacuum, respectively.
n is the refractive index of TOPAS
α_{mat} is the bulk material absorption loss
E is the electric field component
S_z is the z-component of the Poynting vector.

- Integration of the numerator of equation is performed for the solid material region of TOPAS (A_{mat}), and the denominator is integrated over all regions (All).
- EML as a function of frequency for different values of D_{core} is shown in figure.

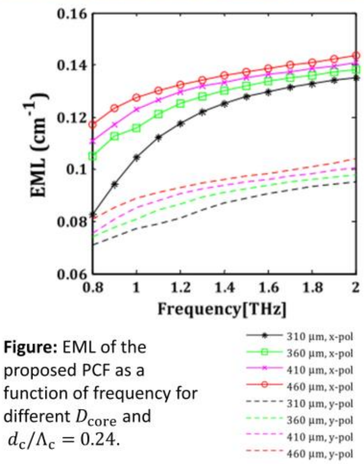


Figure: EML of the proposed PCF as a function of frequency for different D_{core} and $d_c/\Lambda_c = 0.24$.

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Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

So, effective material loss is also an important parameter in designing PCFs which are used for terahertz guidance and is quantified by the following expression.

So, you can have α_{eff} ok. So, that is (ε_0/μ_0) square root of it that is represented by you know to the power of half and then you integrate over the area of the material. So, $n\alpha_{\text{mat}}$ intensity, so our modulus of E^2 is basically the intensity. times dA divided by 2 times integration over all entire area as said dA. So, what are this? So, ε_0 μ_0 are basically the permittivity and permeability of vacuum, n is basically the refractive index of the tuples, α_{mat} is the bulk material absorption loss, E is the electric field component, S_z is basically the z component of the Poynting vector.

So, here you can see there are two integration time terms. So, the integration of the numerator in the equation is basically performed for all the solid material region of the topaz. So, that is called A_{mat} area of the material and the denominator is integrated over the entire area or all the regions. So, you can call it A_{all}. So, this effective material loss which is having a unit of centimeter inverse can be plotted as a function of frequency for different values of core which are mentioned here for different polarization as well.

Photonic Crystals Fibers for Terahertz Guidance

- The calculated α_{CL} for $f =$ 1 THz, D_{core} = 410 μm, and $d_c/\Lambda_c = 0.24$ are 2.24×10^{-5} dB / cm and 1.91×10^{-3} dB / cm for x-polarization and y-polarization modes, respectively.

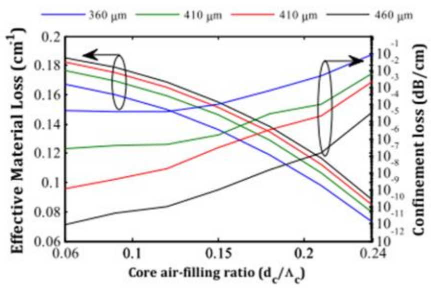

Figure: Confinement loss and EML of the proposed PCF as a function of core air-filling ratio $d_c/\Lambda_c = 0.24$ for different D_{core} at 1 THz.

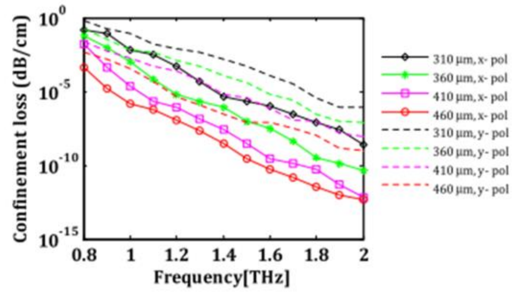

Figure: Confinement loss of the proposed PCF as a function of frequency for different D_{core} and $d_c/\Lambda_c = 0.24$.

Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

fine. So, these are the different core dimensions and different polarization and one thing is kept fixed here that is d by d_c sorry d_c/Λ_c to be 0.24 because that is where you get the largest birefringence. So, the solid line indicates EML of X polarization as you can see here and all these dashed lines are basically telling you about the Y polarizations. the calculated α_{CL} for 1 terahertz frequency for D_{core} of 410 micron d by d_c to be sorry d_c/Λ_c to be 0.24, okay. If you put all these parameters back into this equation, okay, you will get this and this for x and y polarization modes, okay. So this is the plot of confinement loss and effective material loss for this proposed core air filling ratio that is basically d_c/Λ_c to be 0.24 for different core diameters. So, these are the different colors representing different core diameters and the frequency is kept fixed here which is 0.24. at1 terahertz okay. So, this is another figure that shows the confinement loss as a function of the frequency for different core diameters. Again the solid lines shows x polarization, dest lines shows the y polarization and again you have done it for d_c/Λ_c to be 0.24. So, what is important here to notice is that the EML that is the effective material loss decreases with increasing d_c/Λ_c okay that is the core air filling ratio okay. A reverse relationship can be found for ACL okay that is the confinement loss okay and that is α_{CL} and when d_c/Λ_c is increased the amount of air in the core region is also increased therefore more light propagates through the porous core than the core material and as a result your effective material loss is actually getting reduced.

On the other hand, you can say that an increased amount of air in the core is basically leading you to the reduction in the index contrast between the core and the cladding and that is why it is reducing your α_{CL}.

Photonic Crystals Fibers for Terahertz Guidance

- Mode power fraction is another important parameter that describes the amount of power that propagate through different regions and can be expressed by the following expression:

$$\text{Power Fraction} = \frac{\int_X S_Z dA}{\int_{\text{All}} S_Z dA}$$

where X in the numerator is the area of the region of interest, and the denominator is the total area.

- It is evident that at a constant frequency, the fraction of mode power in the air core can increase by increasing the value of D_{core}.

- This is due to the expansion of air portions in the core region with increasing D_{core}.

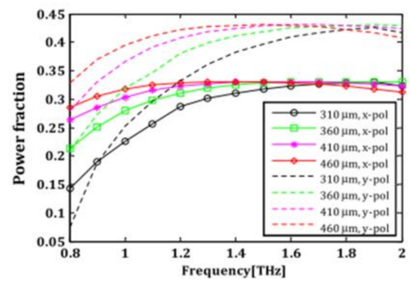

Figure: Fraction of mode power in the core air holes of the proposed PCF as a function of frequency for different different D_{core} and $d_c/\Lambda_c = 0.24$.

Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

So, the another important parameter is mode power fraction that basically describes the amount of power that propagate through different regions and it can be expressed by this expression that is integration over the area of that particular region. interest divided by the total area. So, what is S_z as I mentioned earlier it is the z component of the pointy vector and once you plot it.

So, this is the fraction of mode power in the core air holes of the proposed PCF as a function of frequency. for different D_{core} values and different polarization and this is that ratio core air hole ratio that has been maintained. So, what is evident here that for constant frequency for any frequency. The fraction of mode power in the air core can increase with the increase in the value of D_{core} that is correct and this is due to the expansion of the air portion in the air in the core region when you increase D_{core}. So, here also you can see that with f equals 1 terahertz and if you choose D_{core} to be 410 that is this blue one ok and if you choose this value like.

no I think all these values are for d_c/Λ_c equals 0.24 okay. So, you can say that about 31 percent okay and 37 percent of total power propagates. So, 31 percent for typically x polarized and 37 percent for y polarized right. So, that is how you can interpret this particular graph.

Photonic Crystals Fibers for Terahertz Guidance

- Bending loss analysis is very important for realizing a PCF in practical applications.
- When a fiber is bent, some waves tend to diffuse outward in the direction of the bend and as a result, bending loss occurs.
- Use the conformal transformation method where a bent PCF can be represented as an equivalent straight one with a modified effective refractive index.
- The following expression has been used to represent the equivalent effective refractive index of the straight PCF:

$$n_{\text{eq}}(x, y) = n(x, y)\exp\left[1 + \frac{x}{R}\right]$$

$n_{\text{eq}}(x, y)$: Refractive Index of equivalent straight PCF
$n(x,y)$: Original refractive index of the PCF
R: Bend radius
x: Distance from center of the PCF

Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

Bending analysis or bending loss analysis is also another important parameter for realizing PCFs in practical application. So, when a fiber is bent some waves tend to diffuse outward in the direction of the bend and that is when a bending loss will take place.

so it is a bad thing, so we need to stop it. So, using the conformal transformation method where a band PCF can be represented by you know equivalent straight one with a modified effective refractive index. So, the following expression can be used there to represent the equivalent refractive index, effective refractive index of the straight PCF, you can write n_{eq}(xy), so that is a refractive index of the equivalent state PCF. So, you have n(x,y) that is the original refractive index of the PCF and then you have exponential 1 + x/R, R is the band radius and x is basically the distance from center of the PCF. So, here you can see the figure, this figure shows bending loss of the proposed PCF as a function of the bend radius for y polarization and we have also they have also considered different values of d_{core} ok.

Photonic Crystals Fibers for Terahertz Guidance

- Figure shows the bending loss of the proposed PCF as a function of the bend radius for the y-polarization mode and different values of D_{core}.
- Either increasing the bending radius or core diameter bending loss can be reduced.
- The reason is that both a large bend radius and D_{core} permit a wider space for the propagation of the guiding mode.
- Therefore, guiding waves less tend to diffuse.
- With for $f = 1$ THz, $D_{\text{core}} = 410$ μm, and $d_c/\Lambda_c = 0.24$, and a bend radius of 1 cm, the bending loss was found as about 9.62×10^{-2} dB / cm for the y-polarization mode.

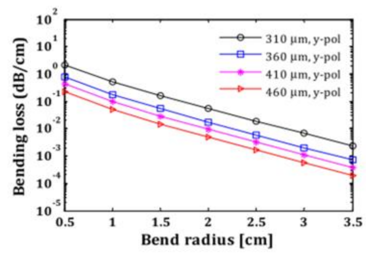

Figure: Bending loss of the proposed PCF as a function of bend radius for different different D_{core} and $d_c/\Lambda_c = 0.24$.

Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

So, what do you see either increasing the bend radius or if you increase the core radius, you can reduce your pending loss. this way you are for each of them you are increasing the band radius you can reduce the bending loss and for one particular core radius you can see which has got the lowest one this triangle which is the largest D_{core}. So, that way it can help. What is the reason? The reason is that both at large band radius and large D_{core} will permit a wider space for the propagation of the guided modes. Therefore the guiding modes will you know tend less to get diffused. So, you can actually find that for f equals 1 terahertz and if you choose D_{core} equals 410 micron and for this particular value of d_c/Λ_c and if you take band radius equals 1 centimeter, you can estimate the band loss to be 9.62×10^{-2} dB per centimeter for the y polarization modes.

Photonic Crystals Fibers for Terahertz Guidance

- Dispersion plays a vital role when PCFs are implemented for practical applications since it indicates the amount of pulse spreading.
- Very small dispersion with low dispersion variation is particularly suitable for the effective transmission of broadband waves.
- As previously mentioned, the refractive index of TOPAS is constant over a wide range of frequencies.
- Therefore, induced material dispersion will be negligible and the overall contribution will be for waveguide dispersion only.
- Waveguide dispersion can be expressed by the following expression: $\beta_2 = \frac{2}{c}\frac{dn_{\text{eff}}}{d\omega} + \frac{\omega}{c}\frac{d^2 n_{\text{eff}}}{d\omega^2}\ \text{ps}/\left(\frac{\text{THz}}{\text{cm}}\right)$

where ω is the angular center frequency $\omega = 2\pi f$, f is the operating frequency, n_{eff} is the effective refractive index, and c is the speed of light.

Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

Dispersion also plays an important role when PCFs are implemented for practical application since it indicates the amount of pulse broadening. So, very small dispersion or you can say with very with low dispersion variation is particularly suitable for you know the effective transmission of broadband waves. So, as we have discussed before the refractive index of TOPAS is constant over a wide range of frequencies. Therefore, you know the induced material dispersion in this case will be negligible and the overall dispersion overall contribution to the dispersion will come from waveguide dispersion only. So, the waveguide dispersion can be expressed using this particular expression where β_2 can be written as $(2/c)$ $(dn_{\text{eff}}/d\omega)$+$(\omega/c)$ $((d^2\, n_{\text{eff}})/d\omega^2)$ the second order derivative the the unit will be picosecond per terahertz per centimeter ok, where ω is basically the angular central frequency. So, ω equals 2πf, f is the operating frequency, $n_{\text{effective}}$ is nothing but the effective refractive index for the particular mode and c is the speed of light.

Photonic Crystals Fibers for Terahertz Guidance

- Figure shows the dispersion profile of the proposed PCF as a function of frequency.
- It can be seen that both x-polarization and y-polarization modes show very low and flattened dispersion over the entire band of interest (0.9– 1.8 THz).
- In this frequency range, the variation of dispersion is about 0.97 and 1.42 ps/THz/cm for x-polarization and y-polarization, respectively.
- From the inset of Figure, it can be observed that for frequencies higher than 1.2 THz, the proposed PCF exhibits lower dispersion variations.
- The dispersion variations in the frequency band of 1.2– 1.8 THz are about 0.51 and 0.63ps/THz/cm for x-polarization and y-polarization, respectively.

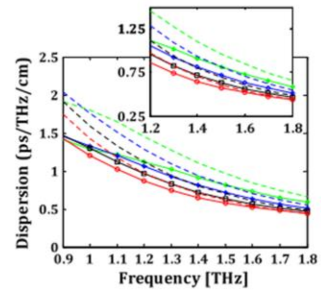

Figure: Dispersion of the proposed PCF as a function of frequency for different different D_{core} and $d_c/\Lambda_c = 0.24$.

Source: M. R. Hasan *et al.*, Polarization-maintaining low-loss porous-core spiral photonic crystal fiber for terahertz wave guidance. Applied optics, 55(15), pp.4145-4152, 2016.

So, here this particular figure shows the dispersion profile of the proposed PCF as a function of frequency and it can be seen that both x and y, so solid one shows x polarization, the dust one shows y polarization. In both case you can see that you know very low and flattened dispersion over the entire band of interest that is from starting from 0.9 to 1.8 terahertz. And in this frequency range the variation of dispersion is about 0.97 and 1.42 picosecond per terahertz per centimeter for case of x polarization and y polarization respectively. You can also look into this insert it can be clearly seen that for frequencies higher than 1.2 okay they actually this particular PCF exhibits very low dispersion variation.

So, the dispersion variation in this band 1.2 to 1.8 terahertz is only about 0.51 and 0.63 picosecond per terahertz per centimeter for the case of x polarization and y polarization respectively. So here it is worth mentioning that the x polarization mode offers lower dispersion than that of the y polarization mode over the entire frequency band. And this is obvious since in contrast to the y polarization mode, a majority of the mode power is basically confined inside the core for the case of y polarization. The proposed structure will also offer relatively low effective material loss and very small confinement loss, small dispersion and low bending loss for the optimal design parameters. The structure is manufacturable due to its realistic size and it also consists only circular air holes in both core and cladding region.

Therefore, you know it is obvious that the proposed fiber can become a potential candidate for effective delivery of polarization maintaining terahertz wave which is going to be having a lot of application in 6G technologies coming ahead.

So, with that we will be concluding our lecture, we will be starting our discussion on designing a mirror, waveguide and cavity in the next lecture. So, if you have got any queries regarding any part of this lecture, you can drop an email to this particular email address, but mention MOOC, photonic crystal and the lecture number on the subject line. Thank you. Thank you.