Lec 36: Next Generation Devices based on Photonic Crystals

Hello students, welcome to lecture 36 of the online course on Photonic Crystals Fundamentals and Applications.

Lecture Outline

- **Next Generation Devices based on Photonic Crystals**
  - **Multiplexers**
- **Next Generation Devices based on Photonic Crystals Fibers**
  - **Lasers**
  - **Polarization Splitters**

Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

Today's lecture we will be discussing about some next generation devices based on photonic crystals. Here is the lecture outline, we will have discussion about you know how to develop multiplexers based on photonic crystals and then we will also look into two interesting devices lasers and polarization splitters which are developed based on photonic crystal fibers.

Photonic Crystals based Multiplexers

Photonic Crystals based Multiplexers

- On-chip ultra-high density optical interconnects in photonic integrated circuits are desired to meet the increasing demand for huge data transmission, especially in data center networks.
- Multiplexing technologies like wavelength division multiplexing (WDM), mode division multiplexing (MDM), and polarization division multiplexing (PDM) are used to increase the data link capacity by allowing parallel data transmission with multiple channels.
- WDM has been the most widely used among these technologies, which can multiplex multiple channels using different wavelengths.
- However, it supports limited channels due to the available wavelength bandwidth density.
- Moreover, the system cost and complexity increase with the number of channels, as each channel requires individual laser sources.
- In recent years, the research interest in MDM has grown since it can further enhance the capacity of optical interconnects by allowing data transmission using modes of the same wavelength, reducing system size and complexity.
- An efficient way to increase bandwidth capacity is by using hybrid WDM-MDM technology, which combines the n-wavelength channels of WDM with m-mode channels of MDM, resulting in total m × n channels.

Source: S. A. Chanu and R. K. Sonkar, Photonic-crystal-based hybrid wavelength-mode division multiplexer for SOI platforms, Applied Optics, 63(21), pp.5728-5737, 2024.

So, let us first take the example of photonic crystal based multiplexer. So, you need to know why this particular device is required. on chip ultra high density optical interconnects in photonic integrated circuits are desired to meet the increasing demand for high data transmission and those you typically see in the data center networks.

Now, there are different multiplexing technology. Multiplexing actually helps you to send Now lot of data together, so you can actually use wavelength division multiplexing where different wavelengths carry different signals okay. You can also have mode division multiplexing where different modes are used for multiplexing. Multiplexing means you know you would add up lot of information which do not interfere with each other and they can be passed or travel together and then at the receiver end you can separate out those information.

You can also have polarization division multiplexing where two orthogonal polarization basically can carry your data. You can also look for different complex modulations or multiplexing schemes, right. So, these are the most popular multiplexing technologies like WDM, MDM and PDM. So, they can be used to increase the data link capacity that allows parallel transmission with multiple channels. Now, of all this WDM is the widely used one because in this case you can actually multiplex multiple channels using different wavelengths.

However, it supports limited channels due to the available wavelength bandwidth density. So, the operational wavelength range is narrow and you have to have certain channel spacing. So, that actually limits the number of channels that you can support. Moreover, the system cost and complexity will increase with the number of channels as each channel will require different individual laser sources. In the recent years, the research interest in MDM has grown, that is mode division multiplexing has grown since it can further enhance the capacity of the optical interconnects by allowing data transmission using modes of the same wavelength.

Thus, it can reduce the system size and complexity. So an efficient way to increase bandwidth capacity will be by using hybrid WDM MDM technology, okay.

Photonic Crystals based Multiplexers

- This technology can increase the channel capacity of the on-chip optical interconnects with an additional design degree of freedom without increasing the chip area as well as the loss, which is caused by the complex interconnects of increased waveguide crossings.
- Periodic structured, i.e., sub-wavelength grating (SWG)- and photonic crystal (PhC)-based devices, have been drawing attention for photonic integrated circuits because of their unique abilities to control the flow of light with low loss and compact device size.
- PhCs are more commonly used, which provide in-plane confinement of light with negligible bending loss and also exhibit wavelength dependence and polarization dependence properties.
- PhCs on the silicon platform can be easily fabricated using the existing complementary metal-oxide semiconductor technology, and it also provides a lesser footprint than its conventional counterparts.
- *Let us discuss a compact 2D PhC-based 12-channel hybrid WDM-MDM device on a silicon-on-insulator (SOI) platform.*

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Source: S. A. Chanu and R. K. Sonkar, Photonic-crystal-based hybrid wavelength-mode division multiplexer for SOI platforms, Applied Optics, 63(21), pp.5728-5737, 2024.

That means you have wavelength division multiplexing combined with mode division multiplexing, okay. So you can say that if there are n channels for WDM. you can combine that with M mode channels of MDM.

So, altogether you can create M cross N number of channels for data transmission. So, this technology can increase the channel capacity of the on-chip optical interconnects with an additional design degree of freedom that you have seen here without increasing the chip area as well as the loss, okay. So usually whenever you make complex interconnects the number of waveguide crossing increases and you will have more number of losses. So here you can actually have you know without increasing the loss and the cheap area you can still increase the channel capacity. So periodic structures such as sub-wavelength grating and photonic crystal based devices have been you know catching the attention for photonic integrated circuits mainly because of their abilities to control the flow of light with little loss and also they can have compact device size.

So, that is where you know photonic crystal whenever you talk about periodic structure a very obvious promising candidate is photonic crystals, right. So, photonic crystals, photonic crystals are more commonly used which can provide you in-plane confinement with very minimal or you can say negligible bending loss and also they can exhibit wavelength dependence and polarization dependence properties. So, in that way you can actually use photonic crystal as a you know very important platform. And then if you make silicon you make photonic crystals on silicon platform that can be easily fabricated right using the existing CMOS technologies. So, it can also provide you know lesser footprint as compared to the conventional counterparts.

Photonic Crystals based Multiplexers

- The proposed device utilizes two bi-directional micro-ring resonator (MRR) arrays for filtering three-wavelength channels and cascaded asymmetric directional coupler (ADC) regions for multiplexing four-mode channels.
- The designed MRR-based wavelength drop filter can work bi-directionally, providing two drop ports from which two similar wavelengths can be dropped separately.
- The two bi-directional MRR arrays resulted in four single-mode (SM) dropped waveguides.
- These waveguides combined into a bus waveguide with different widths using cascaded ADC regions separated by adiabatic taper regions in between.
- The bi-directional nature of the MRR provides a simple configuration with a compact device size.

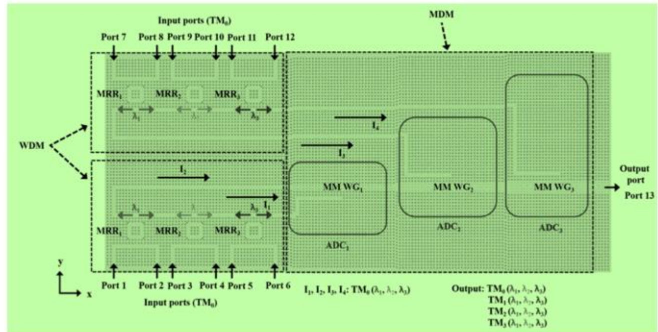

Figure: Device structure of the proposed hybrid WDM-MDM multiplexer.

Source: S. A. Chanu and R. K. Sonkar, Photonic-crystal-based hybrid wavelength-mode division multiplexer for SOI platforms, Applied Optics, 63(21), pp.5728-5737, 2024.

So, we will briefly discuss we will not go into too much of details because it may be very complicated for the newcomers to this field. So, we will briefly discuss this compact 2 dimensional photonic crystal based 12 channel hybrid WDM MDM device. So, it is a wavelength division multiplexing along with mode division multiplexing device on silicon on insulator platform. So, here is the source for this particular work if you are interested I have given the complete source. You can go through this paper and see what kind of design is been done here in more details.

So, the device is supposed to create 12 channels as you can see 12 hybrid channels. So what they are doing, the proposed device will utilize two bidirectional micro ring resonator array. So these are called ring resonators. So you have two bidirectional micro ring resonators array for filtering three wavelength channels and cascaded asymmetric directional coupler. regions for multiplexing 4 mode channels.

Photonic Crystals based Multiplexers

- Figure shows the proposed PhC-based 12-channel hybrid WDM-MDM multiplexer, which consists of two three-channel MRR-based WDM multiplexers and a four-channel ADC based MDM multiplexer.
- The design has 12 input ports (port 1 to port 12), and one output port, i.e., port 13.
- Both the MRRs and the ADCs work with TM polarization modes since the PhC used for the design results in a bandgap only for TM polarization.

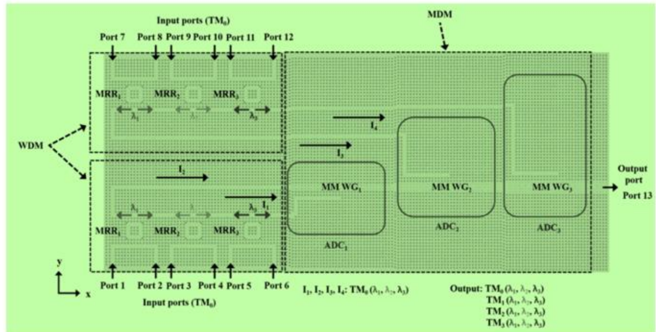

Figure: Device structure of the proposed hybrid WDM-MDM multiplexer.

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Source: S. A. Chanu and R. K. Sonkar, Photonic-crystal-based hybrid wavelength-mode division multiplexer for SOI platforms, Applied Optics, 63(21), pp.5728-5737, 2024.

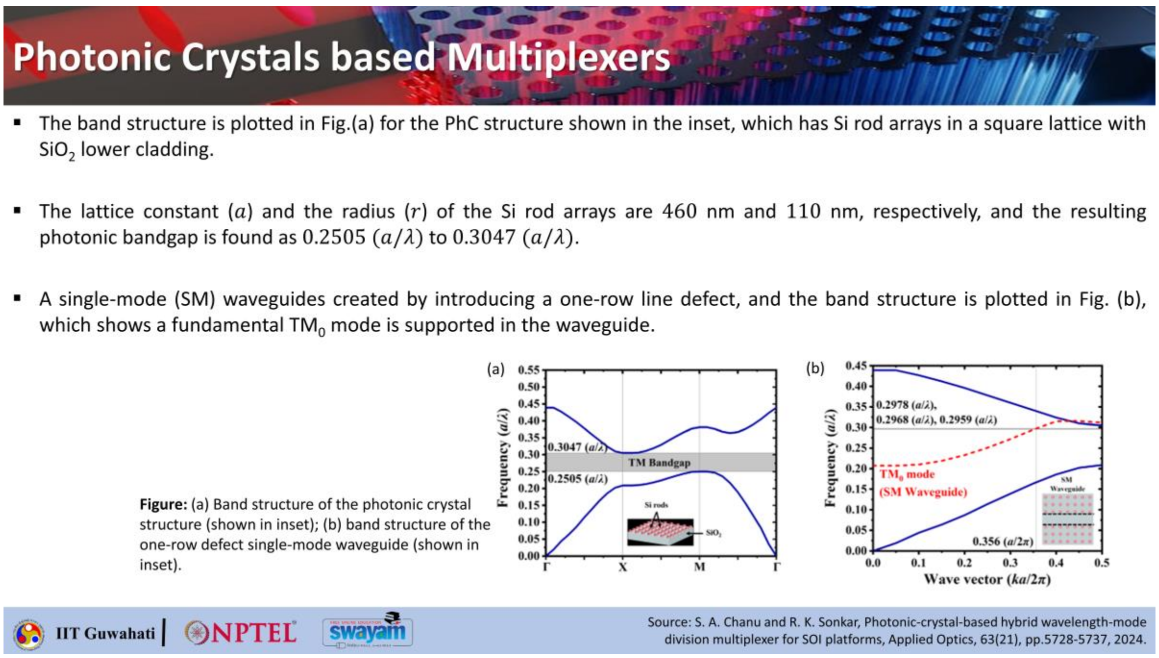
So, that is where 3 cross 4 you are getting 12 hybrid channels. So, we will mainly focus on how these three wavelength channels are created. So, this particular designed micro ring resonator based wavelength drop filters. So, these are called drop filters because you can actually bring a stream and then one particular wavelength will get drop. So, they can work bidirectionally providing 2 drop ports for which 2 similar wavelengths can be dropped separately, ok.

So, the 2 bidirectional MMR arrays will result in 4 single mode dropped waveguides, ok. So you can see here we have numbered the ports. You can start from here itself, port 1, port 2. For this, it is port 3, port 4, port 5, port 6. And then you have port 7, port 8, port 9, port 10, port 11, port 12.

And the final output is coming from port. So, this part is giving you this one and this one is giving you wavelength division multiplexing. This part is little bit more complicated that is giving you more division multiplexing. So, we will mainly focus on only the first part, we will see how the wavelength division multiplexing works in this case. So, this waveguides are combined into a bus waveguide, but different width.

are cascaded into you know here you can see this is the bus waveguide and these are kind of you know they are combined with different widths of asymmetrical directional coupler okay. which are basically separated by adiabatic taper regions in between. So, here you will see there is a taper region because this is narrow, then this is slightly larger, so there are tapers in between. So, this section, this section and this section have three different width. So, you can name this as asymmetrical directional coupler 1, ADC 1, ADC 2 and ADC 3.

So, that way it is a bit complicated. So, there are a couple of interesting devices I encourage all of you to study about directional couplers and you can also study about the adiabatic taper agents in between. these are the part of the mode division multiplexing system, but here we will mainly focus on this part right. So, the bidirectional nature of this MRR micro ring resonators they provide a simple configuration with a compact device size. So, let us go into more details okay.

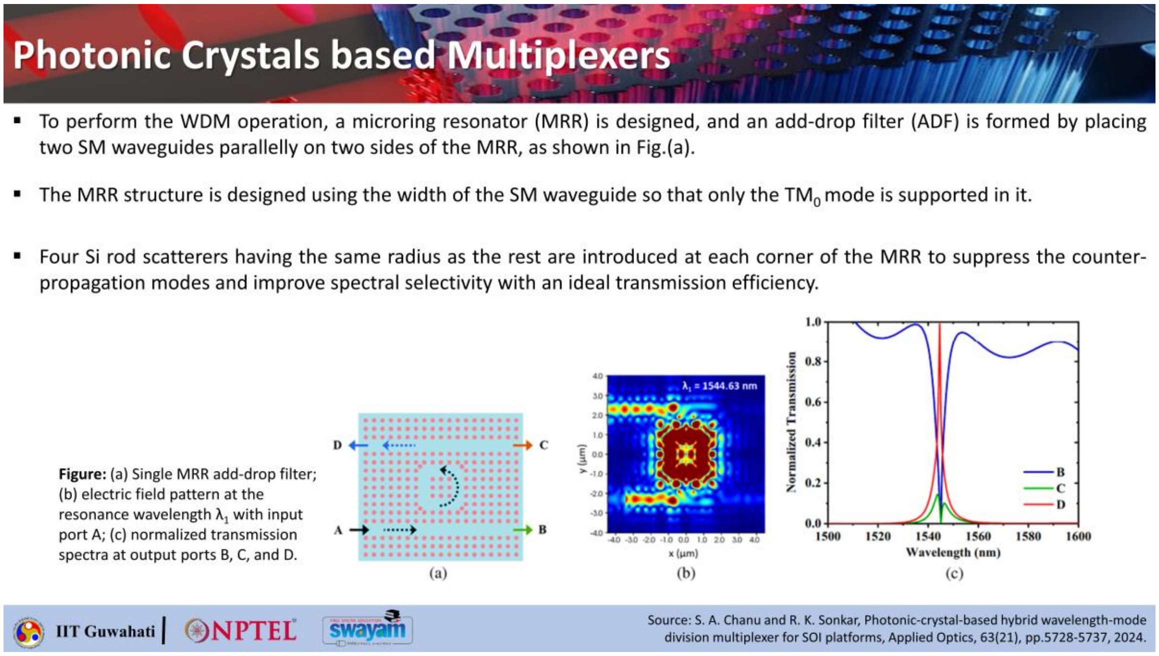


So, as I mentioned this figure is basically telling you about this 12 channel hybrid WDM-MDM multiplexer. So, what do you have here? You have 3, you have basically 2 of this. So, each of these are 3 channel MMR based WDM multiplexers. And, then you have one 4 channel ADC based MDM multiplexer okay, these two things are combined. So, finally you understand that this design has got 12 input ports and 1 output port okay.

And both these MMRs and the ADCs they work with TM polarization since the photonic crystal used in this particular design has bandgap only for TM polarization, clear. So, first of all you can see the basic structure. It is basically shown here as well. These are silicon rods on silica. okay and the band structure is plotted here.

So, this is for the TM mode you can see a beautiful band gap complete band gap existing okay and these are the important points which you have discussed in this course gamma x m gamma okay. So, these are basically for the silicon rod arrays in square lattice with silica as lower cladding. So, here if you consider the parameters the lattice constant a and radius r of the silicon rod arrays are considered to be 460 nanometer and 110 nanometer respectively. And, the resulting band gap is found from you know 0.2505 a/λ to 0.3047 a/λ, okay. So, this is your bandwidth, okay. Authors have not mentioned this as you know band gap to mid gap frequency ratio, but this is how they have expressed it. Now, a single mode waveguide created by introducing a one row line defect that you can see here, okay.

And in that case, when you make this kind of a defect, the band structure is plotted here and it shows TM_0 mode within the band gap which is basically supported in this single mode waveguide.



Now, to perform WDM operation, a micro ring resonator is basically designed. So, this is a micro ring resonator. The name itself tells you it is a ring resonator.

So, it is in the shape of a ring. And a add-drop filter is basically formed. How do you form a add-drop filter? You can take a micro-ring resonator and place two single mode waveguide parallelly on the two sides of the micro-ring resonator which is shown here. So, here you can see A is the input port, B is the through port, C is this one and D is the drop port. So, You can also see the electric field, so this port is not basically used, it is a symmetrical device, so sometime you can use this also as an input port and then this will become through port, this will become your drop port and this will become unused port, okay like that. So, the MRR structure, MRR structure, micro ring resonator.

It's basically designed using the width of the single mode waveguide so that only TM0 mode is supported in it, okay? Because these waveguides are only supporting TM0 mode, right? So what you have done, you basically force silicon rod scatterer having the same radius as the rest are introduced in each corner of the MRR to suppress the counter propagating modes and that also improves the spectral selectivity with an ideal transmission efficiency. So, what are those? So, these extra rods that you see they are basically introduced to improve know selectivity or you can say it to improve suppression of the counter propagating modes and that has actually improved the spectral selectivity. So, this figure shows the electric field pattern at the resonance wavelength of λ_1. So, you can see it enters like this ring resonator and it drops from here. And then here you can actually see the normalized transmission spectrum at output B, C and D.

Photonic Crystals based Multiplexers

- To observe the bi-directionality of the ADF, the incident port is further taken to be port B and ports A, C, and D as the output ports, as shown in Fig. (a).
- The corresponding electric field pattern and the normalized transmission spectra are shown in Figs. (b) and (c), respectively. Maximum field transmission occurs in port C at $\lambda_1 = 1544.63$ nm.

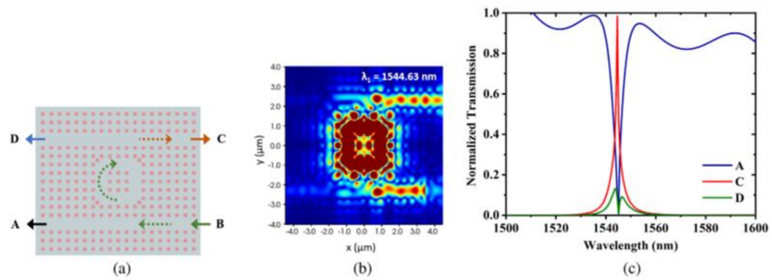


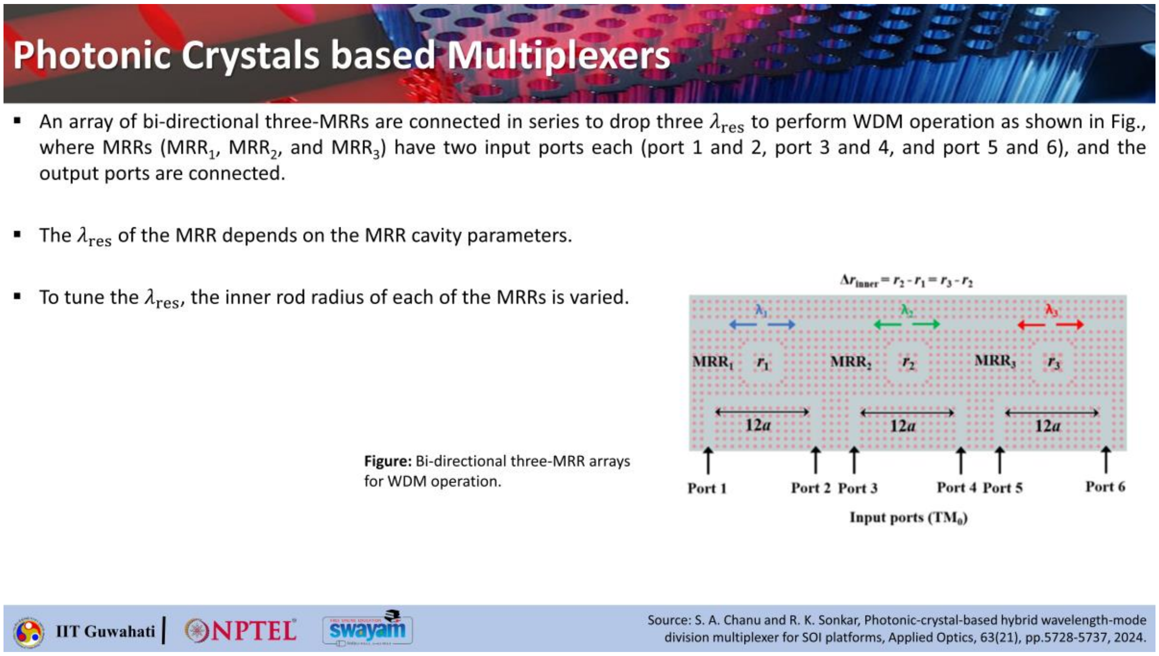
Figure: (a) Single MRR add-drop filter; (b) electric field pattern at the resonance wavelength λ_1 with input port B; (c) normalized transmission spectra at output ports A, C, and D.

Source: S. A. Chanu and R. K. Sonkar, Photonic-crystal-based hybrid wavelength-mode division multiplexer for SOI platforms, Applied Optics, 63(21), pp.5728-5737, 2024.

So, the blue one shows that this particular wavelength is basically dropped and you will see that D has got a sharp peak at this particular frequency right. So, this is called a add drop filter okay and the incident port is A and the exit ports are leveled as B, C, D as I have mentioned already. So, you do not expect anything to come out of this one. So, there are basically very low transmission through this particular port. So, what is the heart and soul of this particular MRR? So, you can see that there is a 3 by 3 inner rod and you have maintained the gap between the single mode waveguide and the MRR to be 2 rows of rod.

So, that is basically the design specification. So the resonant wavelength is found to be 1544.63 and this electric field pattern and spectrum as shown here, which I have already discussed. So, what you can clearly see that at lambda 1, the maximum transmission is happening through port D, that is the drop port in this case. Now, if you want to see the bidirectionality feature of this particular add drop filter, you just change the input port.

So, you now give input through B and then A C and D become your output port. So, what is expected when you send the signal through here, you basically get it coupled through out through C. So, you can see that the transmission at A now the blue color line shows the transmission through A okay and that drops and the output at C significantly picks up okay. So, here you can see the corresponding electric field pattern okay at lambda equals 1544.63 okay. So, that is the wavelength that is being dropped.



Using the same concept, you can actually make an array of this kind of bidirectional split ring resonators sorry bidirectional micro ring resonator based you know air drop filters and you can connect them in series like this. So, here what you see, you see an array of bidirectional three MRRs which are connected in series. So, how do you make the connection in series? You basically have this thing connected and this is your port 1, port 2, port 3, port 4, port 5 and port 6. So, these are your input ports and their output ports are basically connected fine.

So the λ_{res} of the MRR basically depends on the MRR cavity parameters. So this is the cavity parameter, okay. So what they have done here you can see that you have r_1 is the radius of the rods, here r_2 and here r_3. So, that is how you can change the cavity resonance. So, the wavelength that resonates in this cavity will be different from this cavity and then different from this cavity.

So, that is why you modified these three. So, what do you see? There is also another parameter called Δr_{inner} that tells you the difference between r_2 and r_1 that is the difference between the outer and the inner rod radius. Similarly, in this case also you have r_3 minus r_2 like that. So, you can actually plot the dependence of the resonance wavelength on the MRR inner radius. So, these are the three different colors shown for ring resonator 1, 2 and 3 and you can see that as you can increase the radius variation your wavelength is showing a red shift and also the channel spacing can increase

Photonic Crystals based Multiplexers

- The dependence of the λ_{res} on MRR inner rod radius is plotted in Fig., and it can be observed that with the increase in the radius variation (Δr_{inner}), the λ_{res} show a red-shift and increase in the channel spacing.

- To achieve small channel spacing with low crosstalk, Δr_{inner} is chosen as 10 nm, i.e., the inner rod radius of MRR_1 (r_1), MRR_2 (r_1), and MRR3 (r_3) are 110 nm, 120 nm, and 130 nm, respectively, which results in λ_{res} of $\lambda_1 = 1544.63$ nm, $\lambda_2 = 1549.64$ nm, and $\lambda_3 = 1554.69$ nm.

- The obtained channel spacing between λ_1 and λ_2, and λ_2 and λ_3 are 5.01 nm, and 5.05 nm, respectively.

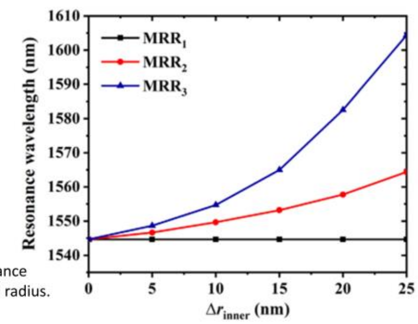


Figure: Dependence of resonance wavelength on MRR inner rod radius.

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Source: S. A. Chanu and R. K. Sonkar, Photonic-crystal-based hybrid wavelength-mode division multiplexer for SOI platforms, Applied Optics, 63(21), pp.5728-5737, 2024.

So, in order to achieve small channel spacing with less crosstalk the authors chose this particular parameter that is Δr_{inner} to be equals 10.

So, that means you know they have considered the inner rod radius r_1 to be 110, then r_2 will be another, you will add 10 to it, so 110, 120 and R_3 is 130, okay. So that way they are able to achieve 3 wavelengths, resonance wavelength, one is 1544.63 nanometer, λ_2 is 1549.64 nanometer and λ_3 will be 1554.69 nanometer, right. So, this way the obtained channel spacing if you see that you know between λ_1 and λ_2 the spacing is almost 5 nanometer, λ_2 and λ_3 also it is almost 5 nanometer right. So, this is how you can actually make multiplexers based on this multi ring resonators. So, the lot of things to be discussed in this particular device but I am not going into too much of details because it is very advanced as you can see here.

We have just discussed this part okay and then you can actually see that this has been coming like this, there are asymmetrical directional coupler, there are tapers and other things that can give you this mode division multiplexing. So, if you are interested you can read this paper in details and understand how this can be used in developing this sort of devices.

So, as a part of this course I am just introducing how you can make a drop filters based on photonic crystal slabs okay and all this basic concepts which can be used for applied application okay.

Photonic Crystals Fibers based Lasers

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Photonic Crystals Fibers based Lasers

- One of the fastest growing and most promising applications of optical fiber is in high-power fiber lasers.
- In the past few years, fiber lasers have evolved from low-power systems for niche applications into challengers to the traditional high-power industrial lasers for materials processing.
- Fiber lasers are gaining market share at a strong pace and are projected to be the industry standard within a few years for marking, printing, cutting and welding.
- Their advantages are low operating costs, high beam quality and high efficiency in a maintenance-free format with a small footprint and low weight.
- In particular, they offer a superior beam quality compared with other laser systems for power levels in the kilowatt range.
- This improves precision and processing speeds for industrial materials processing systems and introduces the possibility for achieving extreme power levels by combining multiple lasers.

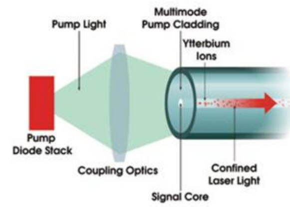
IIT Guwahati | NPTEL swayam Source: J. Limpert *et al.*, Extended single-mode photonic crystal fiber lasers, Optics express, 14(7), pp.2715-2720, 2006.

The next topic would be now photonic crystal fiber based lasers okay. So, one of the fastest growing and most promising application of optical fiber is basically in high power fiber lasers. So, in the past few years fibre lasers have evolved from you know low power systems for very niche applications to challengers to the traditional high power industrial lasers that are used for material processing, is not it. So, fibre lasers are basically gaining the market share now at a very high rate or high speed you can say and they are projected to become the industry standard within few years for marking, printing, cutting and welding.

So, all kind of material processing tasks. So, their advantages are very low operating cost, high beam quality and high efficiency in a maintenance free format that is very important with a very small footprint and low weight. So, in particular they can offer superior beam quality as compared to other laser systems for power levels in the range of kilowatts. So this improves precision and processing speed for industrial material processing systems and they also introduces the possibility for achieving extreme power levels by combining multiple lasers.

Photonic Crystals Fibers based Lasers

- **Photonic crystal fiber**: Most promising technology to significantly lift the current power levels.
- This is because of its increased flexibility in single-mode core sizes, the increased numerical aperture of pump cores in double-clad fiber configurations and the high thermal stability of low-loss all-glass structures.
- Gain medium: Rare-earth-doped fiber.
- Optical pump source: Multimode laser diodes
- The active fiber converts the low-beam-quality pump light into signal light with high beam quality (**figure**).
- The pump light can be coupled by free-space optics such as lenses and mirrors or can be delivered in one or more multimode fibers that are fused onto the active fiber.
- The preferred gain medium for high-power lasers is ytterbium, a result of its high efficiency



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Source: https://www.photonics.com/Articles/High-Power_Photonic_Crystal_Fiber_Lasers/a25277

So, photonic crystal fiber is perhaps the most promising technology as you can see to significantly lift the current power levels and this is because of the increased flexibility in single mode core sizes. and the increased numerical aperture of pump cores in double clad fiber configurations and also the high thermal stability of low loss all glass kind of structures.

So, fiber laser based on rare earth doped fiber. can serve as a gain medium and optical pump source typically for high speed sorry high power application okay in the form of multimode laser diodes can provide the energy for the gain medium and the active fiber could convert the low beam quality pump light into a signal light that has got high beam quality right. So, as I mentioned the game medium is rare earth doped fiber and optical source is multimode laser diodes ok. And then what do you have? You can actually see that the active fiber. So, here you have this is the pump diode stack, this is your fiber. So, this is the multimode pump cladding, this is the signal core, this is how where the confined laser light is and you can see some rare earth doped fiber.

So, these are the So, this is the coupling optics that actually focuses the light onto the core. So, this active fiber will be able to convert the low quality pump light into signal light of high quality which we discussed. And the pump light is basically coupled by free space optics such as lenses and mirrors and it can be delivered to one or more multimode fibers that can be fused into the active fiber. So, the preferred gain medium for high power lasers as we mentioned is yttribium because of its very high efficiency, okay.

Photonic Crystals Fibers based Lasers

60 µm core photonic crystal rod-type ytterbium-doped fiber

- A microscope image of the cross section of the 60 µm ytterbium-doped core air-cladding photonic crystal fiber is shown in Figure.
- The cladding consists of a triangular hole structure possessing a $d/\Lambda = 0.19$.
- The core is formed by 19-missing holes surrounded by 4 rings of air holes.

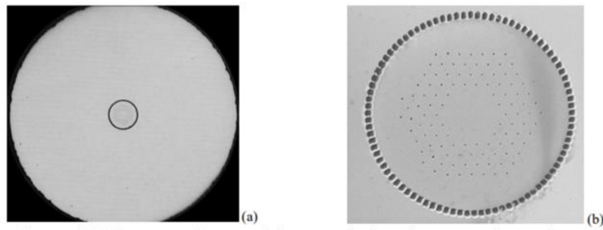


Figure: (a) Microscope-image of the extended-mode-area rod-type photonic crystal fiber and (b) SEM-picture of the microstructured region.

Source: J. Limpert *et al.*, Extended single-mode photonic crystal fiber lasers, Optics express, 14(7), pp.2715-2720, 2006.

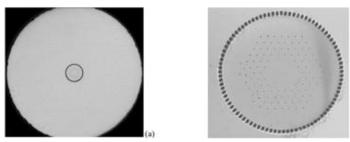
So here we will show you the 60 micrometer code photonic crystal rod type atribium fiber.

So here is the microscope image of the extended mode area rod type photonic crystal fiber and this is the SEM image. you can see this more clearly that it is microstructured, this is where the photonic crystal fiber is okay. So, the cladding basically, so this is the core and this is the cladding it consists of triangular hole structure at $\frac{d}{\Lambda}$. Λ is basically the periodicity, d is the diameter of the hole and it is chosen to be 0.19. okay and the core is basically formed this core is formed by 19 machine holes okay surrounded by you know 4 rings of air holes okay.

Photonic Crystals Fibers based Lasers

60 μm core photonic crystal rod-type ytterbium-doped fiber

- The mode-field diameter of the fundamental mode is $\sim 50\ \mu m$ corresponding to a mode field area of $\sim 2000\ \mu m^2$.
- Figure shows the measured and calculated near-field intensity profile of the single-mode emission of this fiber.



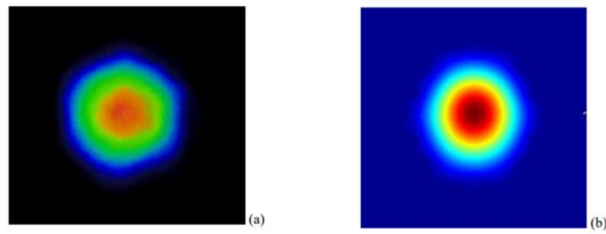


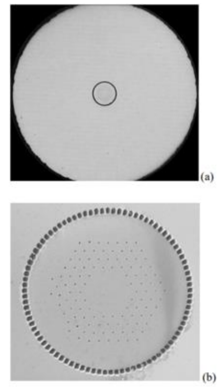
Figure: Measured (a) and calculated (b) near-field intensity profile of the ytterbium doped 60 μm core emission.

Core as you can understand it is microstructured as well and it comprises a balanced composition of ytterbium and fluorine doped glass to match the refractive index as close as possible to the silica index. And in order to obtain producible hole sizes, the resulting refractive index of the doped region is kept slightly below the silica index. And by precise adjustment of effective cladding and the core index to each other, the numerical aperture and thus the number of guided modes can be more precisely defined in this particular case. So, the mode field diameter for the fundamental mode comes out to be around 50 micrometer and that corresponds to a mode field area of around 2000 micrometer square and the figure shows the measured and the calculated near field intensity profile for the single mode emission of this fiber. So, this is the measured and this is the calculated and you can see the strongest field is at the core ok.

Photonic Crystals Fibers based Lasers

<u>60 µm core photonic crystal rod-type ytterbium-doped fiber</u>

- The round inner cladding has a diameter of 175 µm.
- The air-cladding region is formed by silica bridges of ~400 nm width and ~10 µm length leading to a numerical aperture of the inner cladding of ~0.6 at 975 nm wavelength.
- This fiber design has a pump light absorption of 30 dB/m resulting in a very short absorption length of ~0.5 m.
- The fiber diameter is as large as 1.5 mm, thus, the fiber itself has a sufficient rigidity and mechanical stability that no coating material is necessary.
- Furthermore, propagation losses for the fundamental mode can be neglected making the single-transverse-mode guidance in these extended dimensions possible.



Source: J. Limpert *et al.*, Extended single-mode photonic crystal fiber lasers, Optics express, 14(7), pp.2715-2720, 2006.

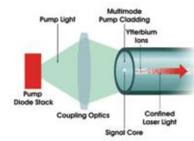
So, this is for this Ytterbium doped 60 micrometer core emission ok. And the round inner cladding that you see has a diameter of 175. So, this is the overall cladding. So, this is having a diameter of 175 micrometer and the air cladding region is basically formed by silica bridges of 400 nanometer width and 10 micrometer length that leads to the numerical aperture of the inner cladding to be around 0.6 at 975 nanometer wavelength okay. So, these are specific to particular this design you can actually go into more details in this particular paper that describes everything about the laser they have designed ok. So, this fiber design has a pumped light absorption of 30 dB per meter that results in a very short absorption length of 0.5 meter right. And the fiber diameter is as large as 1.5 millimeter therefore, the fiber itself is sufficiently rigid okay and it has got mechanical stability, so no extra coating material is needed in this case, okay.

Therefore, propagation losses for fundamental mode can be neglected making single transmission mode guidance in this extended dimension possible.

Photonic Crystals Fibers based Lasers

60 µm core photonic crystal rod-type ytterbium-doped fiber

- To demonstrate the average power handling capability of this fiber design, built up a simple continuous-wave fiber laser.
- The fiber is pumped from both ends by fiber-coupled diode lasers emitting at 976 nm.
- The resonator is formed by one high reflecting mirror and Fresnel reflections on the other end.
- The rod fiber is perpendicularly polished after collapsing the air-holes.
- It has to be mentioned that the rod is water-cooled.
- Actually, the water cooling is not of essential need, because the fiber design could handle the thermal load by its own.
- But any misalignment of the cavity would lead to not extracted population inversion, hence more thermal load, consequently a de-population of the lower laser level and therefore a reduction of pump light absorption.
- This avalanche process could eventually destroy the conversely emitting diodes.



Source: J. Limpert *et al.*, Extended single-mode photonic crystal fiber lasers, Optics express, 14(7), pp.2715-2720, 2006.

So, to demonstrate the average power handling capacity of this fiber, they build up a simple continuous wave fiber laser   So, the fiber is basically pumped from both ends by fiber connected diode lasers which are emitting at 976 nanometer. The resonator is formed by one high reflecting mirror and Fresnel reflection at the other end. So, you basically have a resonator cavity kind of thing and the rod fiber is perpendicularly polished after collapsing the air holes okay.

and it has to be mentioned that the rod is water cooled. So, actually water cooling is not of essential need, but you know the fiber design because the fiber design basically could handle the thermal load on its own ok. But any misalignment of the cavity could lead to not extracted population inversion, hence more thermal load and then consequently you know a depopulation of the lower laser level and therefore reduction of pump light absorption okay. why to risk all these things better you know you do the water cooling right. And this avalanche effect could have essentially destroy the conversely emitting diodes as well.

Photonic Crystals Fibers based Lasers

60 µm core photonic crystal rod-type ytterbium-doped fiber

- **Figure** shows the output characteristics of the high power short-length fiber laser.
- At a launched pump power of 425 W we achieved 320 W of laser output power with a slope efficiency of 78%.
- This value corresponds to an extracted power per unit length of 550 W/m.
- The high efficiency, which is comparable to the most efficient ytterbium-doped fiber lasers, is in contrast to large-core multimode fibers forced to operate single-mode, e.g. by applying bending losses, where the efficiency penalty increases which increasing core diameter.

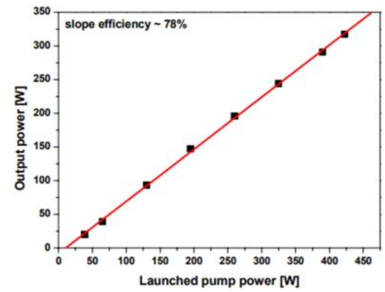


Figure: Output characteristics of the high power short-length rod-type fiber laser.

Source: J. Limpert *et al.*, Extended single-mode photonic crystal fiber lasers, Optics express, 14(7), pp.2715-2720, 2006.

So, here you can see the output characteristics of the high power short wavelength fiber laser. So, this is the launched power and this is the output power ok and at launch power of 425 watt, you can actually see you are getting around 320 watt of laser output, which because the slope has got almost 78 percent efficiency, right. So, this value basically corresponds to an extracted power per unit length of something like 550 watt per meter. So, this is very high efficiency which is comparable to the most efficient atrium doped fiber laser and this is in contrast to the large core multimode fibers forced to operate at single mode by applying say bending losses where the efficiency penalty increases which increases the core diameters.

Photonic Crystals Fibers based Polarization Splitters

Photonic Crystals Fibers based Polarization Splitters

- Polarization beam splitters (PBS), that can separate the two orthogonal polarization states of incoming light.
- PBS IS one of the essential components in optical fiber communications and integrated photonics.
- A disadvantage of conventional fiber-based polarization splitters, however, is that a long coupler length (> a few cm, typically) is required because the birefringence of conventional glass fibers is small.
- Photonic crystal fibers (PCFs), also called microstructured fibers or holey fibers, have attracted significant research attention because they provide extra degrees of freedom in manipulating optical properties.

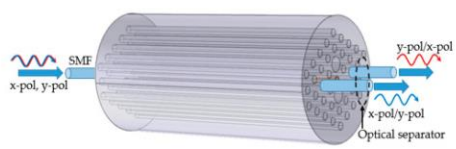


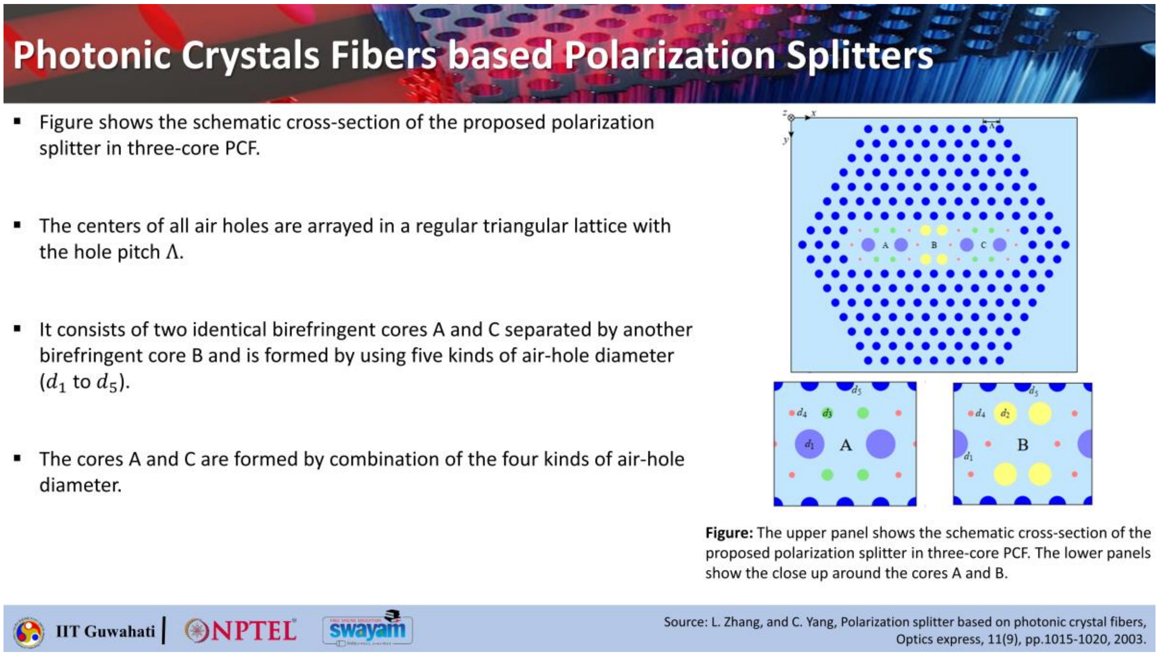
Figure: Schematic diagram of the PBS operation.

Source: L. Zhang, and C. Yang, Polarization splitter based on photonic crystal fibers, Optics express, 11(9), pp.1015-1020, 2003.

So, the last topic that we will be covering that is you know how to design polarization splitters based on photon crystal fibers. So, polarization beam splitters as the name suggests, they separate the two orthogonal polarization states of the incoming light.

Here you can see the schematic doing that, okay. So, this is a single mode fiber getting x polarization and y polarized light together and you can actually split them out or separate them out in the two output states. fibers. So, what is PBS? Polarization beam splitter is an essential component in fiber optic communication as well as in integrated optics. So, a disadvantage of conventional fiber based polarization splitter, however, is that a long coupler length. when I say long here it is in the order of few centimeters is typically required because you know the bifringence of the conventional fiberglass is very small.

So, your overall device length becomes few centimeter. But if you take you know So, photon and crystal fiber or they are also called microstructured fibers or holy fibers which we have discussed earlier in this course, they have attracted a lot of attention to replace this conventional fibers because they actually provide an extra degree of freedom in manipulating the optical properties, right. So, as I mentioned here the schematic shows the operation of a polarization beam splitter, So, here is the design of the schematic cross section of the proposed polarization beam splitter in three core photon and crystal fiber, okay. The three cores are A, B and C here, okay. You can see the design taken from this particular reference paper. you can go and read this paper in more details if you are more interested to work in this particular area.



I will briefly tell you how it works. The centers of all air holes are arrayed in a regular triangular lattice with a hole pitch of capital lambda and you can see it consists of two identical birefringent cores A and C which are basically separated by another birefringent core of B and that is formed by using 5 kinds of air hole diameter. So, if you look into this zoomed diagram you can see this is air hole diameter d_1, then here you have d_2, this is d_3, d_4 and d_5. So, you are basically taking help of 5 different air hole diameters to make this birefringent kind of diagram. cores.

So, the core A and C are formed by combination of 4 kind of air hole diameter. So, as you can see d_1, d_3, d_4 and d_5 are used for A and C and for B you are using another type that is d_2. So, the large air holes with diameter D1 are basically placed on left and right side of the cores A and C. So, I am only describing with A because C is exactly the same copy of this one. However, the core B is basically formed by combination of four kinds of air holes, you can see here.

Photonic Crystals Fibers based Polarization Splitters

- The large air holes with diameter d_1 are placed in the left and right around the cores A and C.
- The core B is also formed by combination of the four kinds of air-hole diameter.
- The large air holes with diameter d_2 are placed in the above and below around the core B.
- The operation of this splitter is based on the fact that:

  The difference in the effective refractive indices of the horizontally polarized (x-polarized) and the vertically polarized (y-polarized) modes could be increased by using highly birefringent PCF structures shown in lower panels of Figure.

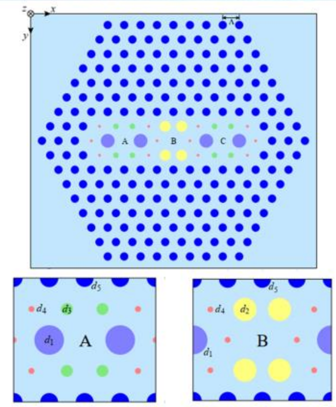


Figure: The upper panel shows the schematic cross-section of the proposed polarization splitter in three-core PCF. The lower panels show the close up around the cores A and B.

Source: L. Zhang, and C. Yang, Polarization splitter based on photonic crystal fibers, Optics express, 11(9), pp.1015-1020, 2003.

So, what is not appearing here is d_3. So, the large air holes with diameter d_2 are basically placed in the above and below the core 2. So, this way you can make it birefringent. So, the operation of the splitter is based on the fact that the difference in the effective refractive index of the horizontally polarized that is X polarized and the vertically polarized that is Y polarized modes could be increased by using highly birefringent photonic crystal fiber structures which are basically shown here. So, the large difference can be used for polarization sensitive devices that are based on the phenomena of resonant tunneling. So, in course A and C, the effective indices of X polarized modes are basically smaller than those of the Y polarized mode.

Photonic Crystals Fibers based Polarization Splitters

- This large difference can be used for polarization-selective devices based on the phenomenon of resonant tunneling.
- In cores A and C, the effective refractive indices of *x*-polarized mode are smaller than those of *y*-polarized mode.
- On the other hand, in core B, the effective refractive index of *x*-polarized mode is larger than that of *y*-polarized mode.
- The structure of core B is so designed that its *x*-polarized mode is almost resonant with the *x*-polarized mode of the outer cores A and C.
- Due to the large difference between the effective refractive index of *y*-polarized mode in core B and those in cores A and C, the *y*-polarized mode of core B will be completely non-resonant with those of the outside cores A and C.

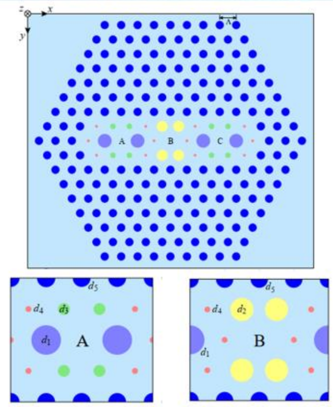


Figure: The upper panel shows the schematic cross-section of the proposed polarization splitter in three-core PCF. The lower panels show the close up around the cores A and B.

Source: L. Zhang, and C. Yang, Polarization splitter based on photonic crystal fibers, Optics express, 11(9), pp.1015-1020, 2003.

And on the other hand, in the case of core B, the effective index of the x polarized mode is basically larger than the y polarized modes. So, these are all dependent on the air holes. So, air hole larger the air hole you will have reduced effective refractive index. So, the structure of B is designed in such a way that its x polarized mode is almost resonant with the X polarized mode of the outer course A and C. And due to the large difference between the effective refractive indices of Y polarized mode in core B and those in cores A and C, the Y polarized mode of core B will be completely non-resonant with those of the outside cores that is A and C.

Photonic Crystals Fibers based Polarization Splitters

- The operation of this polarization splitter can also be explained in terms of the supermodes of the three-core directional coupler.
- If the individual isolated cores of the coupler are single moded, the coupled structure supports three modes, two symmetric and one antisymmetric modes.
- Let $n_{\text{eff},1}$, $n_{\text{eff},2}$, and $n_{\text{eff},3}$ represent the effective refractive indices of the two symmetric and the one antisymmetric modes, respectively, for each of the polarization states.
- If we choose the parameters of the PCF to satisfy the condition:

$$(n_{\text{eff},1} - n_{\text{eff},3}) = (n_{\text{eff},3} - n_{\text{eff},1})$$

$$i.e. \quad 2n_{\text{eff},3} - n_{\text{eff},1} - n_{\text{eff},2} = 0$$

- The power transfer efficiency from one outside core to another can be maximized.

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Source: L. Zhang, and C. Yang, Polarization splitter based on photonic crystal fibers, Optics express, 11(9), pp.1015-1020, 2003.

So, in that way what happens? The operation of this power splitter can be explained in terms of the super modes of the 3 core directional coupler. So, if the individual isolated cores of the couplers are single moded. the coupled structure will now support say 3 modes, so 2 symmetric and 1 anti-symmetric mode. So, you can consider $n_{\text{eff},1}$, $n_{\text{eff},2}$ and $n_{\text{eff},3}$ as the effective refractive indexes of this 2 symmetric and 1 anti-symmetric mode for each of the polarization states. So, if we choose the parameters of the photonic crystal fiber to satisfy these conditions that $(n_{\text{eff},1} - n_{\text{eff},3}) = (n_{\text{eff},3} - n_{\text{eff},1})$, sorry there is an error here, it should be 1 minus 2 and 2 minus 3 something.

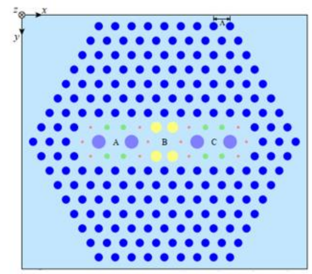
So, I will correct it later on. So, final expression this one is correct. So, $i.e.$ $2n_{\text{eff},3} - n_{\text{eff},1} - n_{\text{eff},2} = 0$. That means the power transfer efficiency from one outside core to another can be maximized.

Photonic Crystals Fibers based Polarization Splitters

- In the proposed configuration, the *x*-polarized modes between the outer cores strongly interact through resonant tunneling, while for the *y*-polarized mode the interaction is much weaker.
- Thus, it is possible to choose the parameters as

$$\left(n_{\text{eff},1} - n_{\text{eff},3}\right)_{\text{x-pol}} \approx \left(n_{\text{eff},3} - n_{\text{eff},2}\right)_{\text{x-pol}} \quad \text{and} \quad \left(n_{\text{eff},1} - n_{\text{eff},3}\right)_{\text{y-pol}} \ll \left(n_{\text{eff},3} - n_{\text{eff},2}\right)_{\text{y-pol}}$$

- Choosing a PCF of length L as: $L = \lambda / \left\{2\left(n_{\text{eff},1} - n_{\text{eff},3}\right)_{\text{x-pol}}\right\}$
- The *x*-polarized mode launched into core A would couple to *x*-polarized mode in core C, on the other hand, the *y*-polarized mode launched in core A would mainly exit from core A, where λ is the operating wavelength.



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Source: L. Zhang, and C. Yang, Polarization splitter based on photonic crystal fibers, Optics express, 11(9), pp.1015-1020, 2003.

So, in this proposed configuration the x polarized modes between the outer cores strongly interact with the resonant through the resonant coupling while the y polarized mode interaction is very weak and thus it is possible to choose the parameters to be like this, here it is correctly done. So, 1 minus 3 will be equal to 3 minus 2, so that is for x pole and also you will make sure that this for y pole is much much smaller.

$$\left(n_{\text{eff},1} - n_{\text{eff},3}\right)_{\text{x-pol}} \approx \left(n_{\text{eff},3} - n_{\text{eff},2}\right)_{\text{x-pol}}$$

$$\left(n_{\text{eff},1} - n_{\text{eff},3}\right)_{\text{y-pol}} \ll \left(n_{\text{eff},3} - n_{\text{eff},2}\right)_{\text{y-pol}}$$

So, if you choose the photonic crystal fiber length to be L equals $\lambda / \left\{2\left(n_{\text{eff},1} - n_{\text{eff},3}\right)_{\text{x-pol}}\right\}$, in that case the X polarized mode that you launch into core A will couple to the X polarized modes in core 3.

And on the other hand, the Y polarized mode that is launched into core A would mainly exit from core A. And here lambda is the operating wavelength. fine.

Photonic Crystals Fibers based Polarization Splitters

- The individual isolated cores of this structure support only *x*-polarized and *y*-polarized fundamental modes in 1550-nm wavelength range.
- As we mentioned in previous section, the necessary condition for obtaining a high- power transfer efficiency between the outer cores is $2n_{\text{eff},3} - n_{\text{eff},1} - n_{\text{eff},2} = 0$, i.e., the effective refractive indices of the supermodes of the coupler must be equally spaced.
- Figure shows the variation of the effective refractive indices of supermodes of the three-core PCF and the value of $2n_{\text{eff},3} - n_{\text{eff},1} - n_{\text{eff},2}$ for the *x*-polarization state as a function of d_2/Λ.

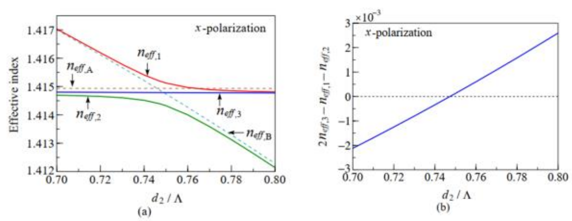


Figure: The variation of (a) the effective refractive indices of the supermodes of the three-core PCF and
(b) the value of $2n_{\text{eff},3} - n_{\text{eff},1} - n_{\text{eff},2}$ for the *x*-polarization state as a function of d_2/Λ.

Source: L. Zhang, and C. Yang, Polarization splitter based on photonic crystal fibers, Optics express, 11(9), pp.1015-1020, 2003.

So, the individual isolated cores of this structure support only x polarized and white polarized fundamental modes in 1550 nanometer wavelength range that we have seen. And as mentioned in the previous section that the necessary condition for obtaining a high power transfer efficiency between the outer core is this equation that means $2n_{\text{eff},3} - n_{\text{eff},1} - n_{\text{eff},2} = 0$.

That means the effective refractive indices of the super modes of the coupler must be equally spaced. So, the difference between the effective index of 1 and 2 and 2 and 3 should be same. So, if you do that you can actually find out this the figure actually shows the variation of the effective indices of super modes.

So, you have this for X polarization. So, it shows for the three core PCF. So, this is basically $n_{\text{eff},2}$, this is $n_{\text{eff},1}$ and this is $n_{\text{eff},1}$, this is $n_{\text{eff},1}$, this is $n_{\text{eff},2}$, this is $n_{\text{eff},3}$ and this is for those modes A and B. So, the second figure shows the value of this ok. So, what do you want you basically want here right. So, from that you can find out what is your d_2/λ. So, you want you have basically plotted this value or this function as a function of d_2/λ ok.

Photonic Crystals Fibers based Polarization Splitters

- The three-core polarization splitter could split two polarization states.
- The PCF parameters are as follows: $\Lambda = 2.0$ µm, $d_1/\Lambda = 0.95$, $d_2/\Lambda = 0.747$, $d_3/\Lambda = 0.3$, $d_4/\Lambda = 0.2$, and $d_5/\Lambda = 0.5$.
- Figure shows the normalized power variation along the propagation distance in the cores A and C.
- It is found that the *y*-polarized mode launched into core A does not couple into the core C, while the *x*-polarized mode completely couples into the core C and the curve of the power transfer versus the fiber length is very smooth.
- The separation of two polarization states is achieved at the propagation distance of $\sim$ 1.93 mm.

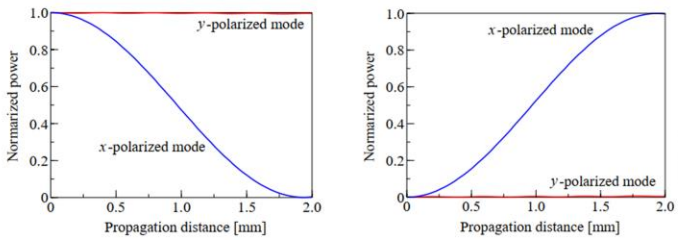
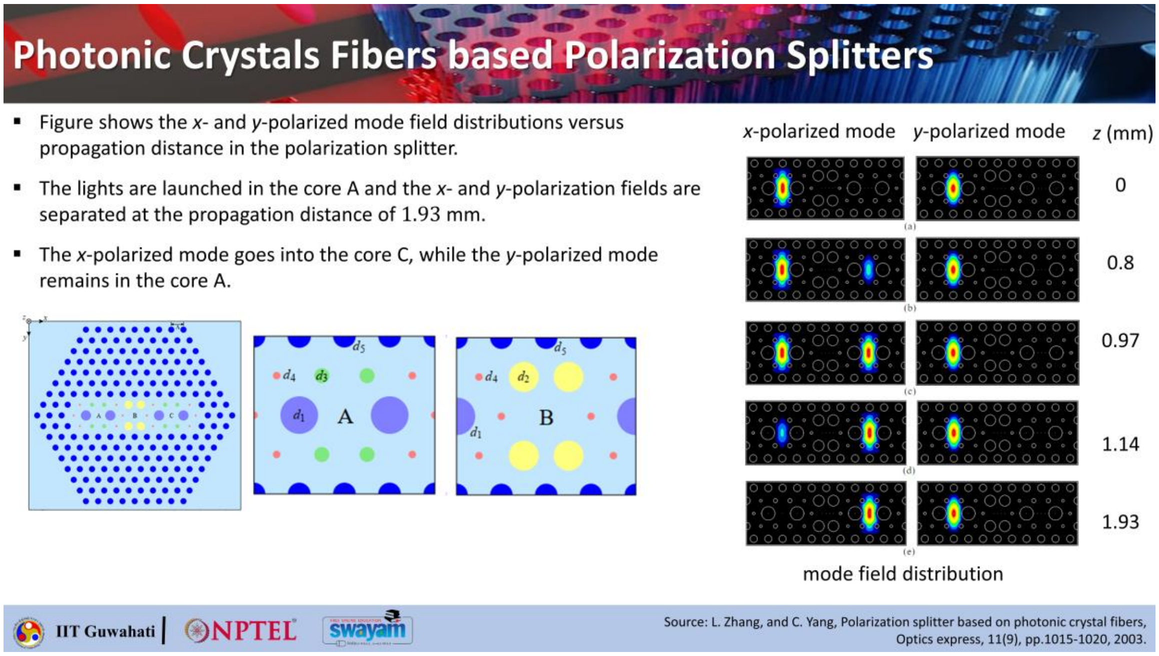


Figure: Normalized power variation along the propagation distance in the cores A and C, respectively.

Source: L. Zhang, and C. Yang, Polarization splitter based on photonic crystal fibers, Optics express, 11(9), pp.1015-1020, 2003.

So, this you have done for exploration state. So, what is important here is that you know in this particular figure as I mentioned the effective indices of the fundamental modes of the isolated course A and B are basically shown as N effective A and N effective B, for both are shown for X polarization. And they are shown as the dashed curves and to obtain the effective reflective index, of the x polarized and y polarized super modes of the three core structure, you have to use a full vectorial mode solver based on finite element method. You can go for more details in this particular journal paper.And here you can see that now this term is becoming 0 at d2 by lambda equals 0.747. what it tells you that at this particular point, the effective indices of x polarized super modes that is n effective 1 will be equal to around 1.415 and for n effective 3, okay it is around for this point yeah it is around 1.414 okay. So, from that you can find out that the coupling length will be roughly along because D2 you know you can find out what is your coupling length L okay and that comes out to be 1.9 millimeter. okay and for the y polarized super modes you can also do the similar kind of exercise and you will see you know for the y polarized super modes of the PCF you can find out the differences between the effective indexes in this of first and the third mode and then third and the second mode and they will show high polarization dependence of the coupler. So, these are the design parameter I am not going to much details of how this has been done. So, just to show you that you know if you consider lambda equals 2 micrometer d 1 by lambda is this d 2 by lambda d 3 by lambda d 4 and d 5. So, these are the parameters that tells you in terms of lambda.



So, once you fix the pitch you can find what are those hole diameters ok. And here you can see basically what I was talking about the y polarized mode. So, if you launch y polarized mode into core A, it does not at all coupled to core C, but then for x polarized mode, it basically you know the power gets transferred completely into C. So, here this is basically for core A, this is for core C. So, x polarized over a distance completely get transferred to C, but y polarized remains same okay.

And the separation of the two polarization states is achieved over a propagation distance of 1.93 to be exact okay, they are considering this particular point. you can actually show you the simulation result as well. So, here is X polarized mode and Y polarized mode.

So, this is A and this is C, A and C. So, there is something through this B, resonant tunneling. So, you can see that Y polarized mode okay simply gets transmitted nothing comes to C but X polarized mode slowly gets completely transferred to C. So, that way you can basically do the polarization beam splitting right. So, your X polarization will now appear at C but Y polarization will remain in core A only, okay. So, that is the whole idea to tell you that you can use photonic crystal fibres for designing this kind of polarization beam splitter or lasers and different application. So, all together I hope it is understood that photonic crystals have lot of applications in designing compact, low loss or even almost lossless devices which are very important for optical communication and they are going to become the backbone of the high speed optical data communication technology that is going to support the ever increasing demand of data rate in the coming days.

So, that completes the discussion of this particular course as well. And thank you for your attention and attending this course. If you have got any query regarding the lectures, you can always drop an email to me even after when the course is over. This is my email address and you mentioned about the photonic crystals, I will be there to handle and help you with your queries. Thank you.