Indian Institute of Science

NPTEL

Photonic Integrated Circuits

Lecture – 14
Lecture Summary

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NPTEL Online Certification Course

Now let us look at an overview of the entire topics that we have seen until now.

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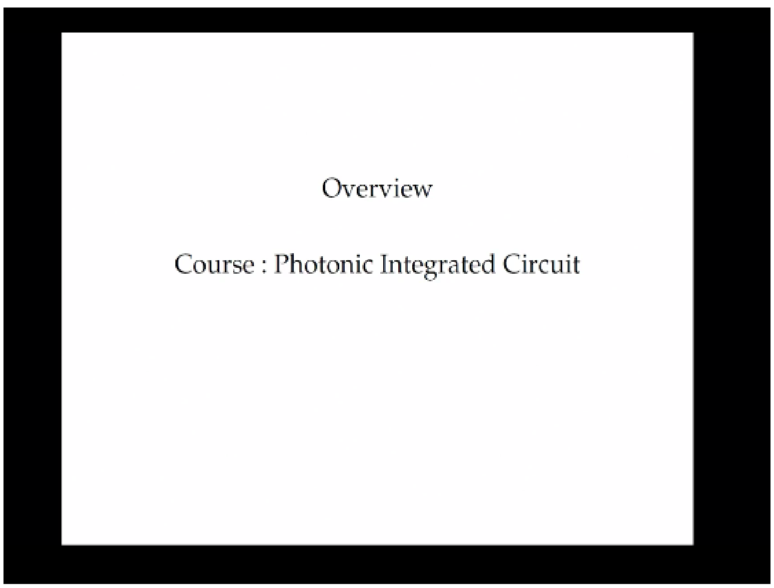

So the subject can be called as overview of photonic integrated circuits.

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Course: Photonic Integrated Circuit	
Module1	Introduction to Integrated optics
	Optical Waveguide Theory- Symmetric Waveguide Theory
	Optical Waveguide Theory- Asymmetric Waveguide Theory
Module 2	Vector Modes
	Optical Waveguide Theory-Channel waveguide
	Directional Coupler-Couple Mode Theory
Module 3	Passive Devices and Beam Propogation Method
	Dynamic Devices
	Integrated optical Systems and Applications
Module 4	Fabrication and Characterisation
	MOEMS
	Ring Resonators
	Photonic Band Gap devices
	Recent Advances

So this is the dot topics that we have covered, so we had four modules of varying the lengths. So we have started with the brief introduction to integrated optics, then we went with mathematically on how light propagates in optical waveguides and in particular symmetric slab waveguides and asymmetric slab waveguides. Then we looked at the actual properties of the modes which are factorial in nature.

Then we looked at what is called the coupled mode theory or the theory that will be useful for studying if there is an couplers and many other phenomena. And of course we also extended the theory to two dimensional or three dimensional waveguides called the channel waveguides which are the real elements, basic elements of integrated optics which can be used to make many, many other devices.

So in module 3 we looked at many passive devices as examples and we looked at the methods to analyze such problems, one particular method that we talked about is called the B propagation method which can be used, it is the semi-numerical method which can be used to study many passive devices which, otherwise could not be analyzed in the direct method. Then the dynamic devices consists of control of the properties of optical waveguides using external effects such as electro optic effect, magnetic optic effect and so on and so forth.

Now of course finally we have seen some examples of integrated systems, applications, optical or communications, optical sensors, and so on and so forth. Finally the module 4 we looked at the various techniques to fabricate these integrated optical devices, then we saw some three emerging topics to say called the optical MOEMS, then the ring resonators, and the photonic band gap devices.

And of course I would like to very briefly mention about the recent advances which we have not covered in this course, which you have hopefully in the future course or some other course you will be able to undertake.

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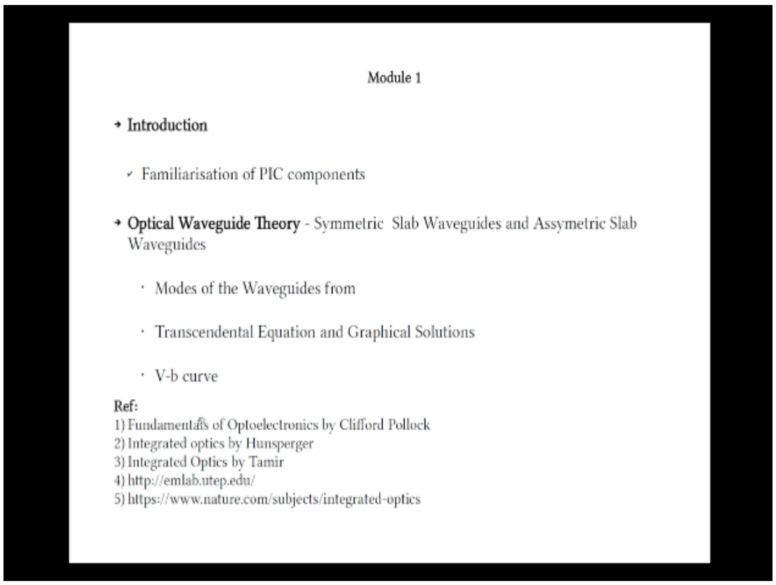

So the first module consisted of the introduction to integrated optics, familiarization of various types of photonic integration with components. Then the various technologies used to various types or devices and so and so forth, they are very broad way not in depth, everything without is much mathematics. So as the example to go deeper into understanding the propagation of light in the waveguides we took up symmetric slab waveguide first, where the, and use the scalar approach to find out the various modes of the optical waveguide.

So wherever that trenchantly equation and we look at various methods to handle that and interpret more importantly and finally in terms of the design we end up in what can be called as a VB curve. So in this case of a symmetric slab waveguide also we have almost the same, we have taken a parallel approaches thereof slab waveguide, but of course we know that is more general and in particular there is a cutoff V number, so to say below which, below such V number, the light is not guided in the asymmetric slab waveguide.

And once again we have seen several properties as a function of asymmetric parameter and so on and so forth. We indicated that the optical waveguide theory or studied in symmetrical slab waveguides is useful in many, many ways in particular it is useful to design the channel waveguides, then of course it is also useful to study the effect of fabrication and its relationship with the design and so on and so forth. There are several general books are mentioned about the integrated optics here.

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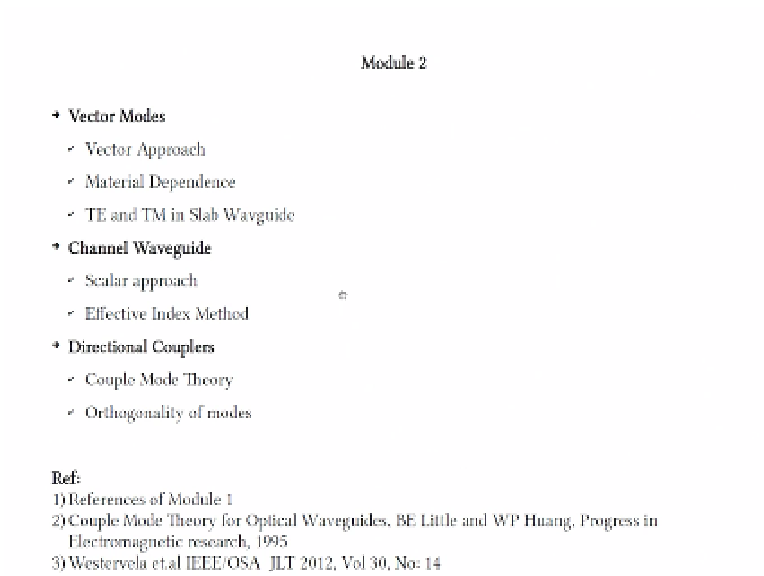

So then the module two, vector modes so we said that the modes are vector in nature where all the components are possible due to the nature the boundary conditions waveguide can support all components of the in principle all components of the electromagnetic field. And of course we could reduce depending on the geometry and many other conditions we can reduce the modes to different ways.

For example, we have TE modes and TM modes in slab waveguide, then hybrid modes the combination of these channel waveguide, then you can talk about the weekly guiding modes, the refractive index difference is very small, then the dependence of these properties on the material characteristics like amaze ultra B uniformity and so and so are important. And of course the polarization characteristics are important in many devices like polarize controllers, isolators and so on and so forth.

As far as the channel waveguide concern is one of the important element of the photonic integrated circuit we have taken a scalar approach to solve this and we have used a method called the refractive index method. So refractive index method consists of conceiving the channel waveguide in two steps, in the first step you have the slab waveguide with width as in of the depth as important parameter.

And we find out the effective refractive index as a symmetric slab wave guide and use that refractive index this part, where the ser step to you take a vertical slab width effective refractive index as the film and of course it depends on the many other factors also depend in give geometry we can split these channel wave guide more effectively into horizontal and vertical waveguides and decide it.

So mathematically we can also take regress approach where you find the fields in all the regions of the channel waveguide at the match the boundaries and finally arrive at a disposition equation like for that scalar asymmetric slab waveguides but if course there is more compulsion and effective index as prove to be very effective in many applications and simplified the design process.

So channel waveguide are now applied to other geometries so when we want to make one the important devices is called the directional coupler it can be said to be the very general multipurpose device which can be applied to many applications like you have make a couplers you can make power dividers you can using the other effects like electro optic effect you can make modulators which as set off by using the directional couplers one of the most important property and striking results is that the power launched into one of the waveguides can be exchanged with the other waveguide even though there is a small amount gab in-between the wave guides.

So and the phenomena is observed to be periodic and we can periodically coupling back and forth between the different waveguides we can take a appropriate length so that you get the required amount of power coupling form one wave guide to the other board we have considered what is called the couple more theory to study this process where the mod field is considered as a super position of the modes of the individual waveguides.

So and apply into the wave equation to obtain the variation of the fields coefficients A and B are in U and B whatever considered are considered to be variables with respect to z and the respects the power exchange process, so we are after substituting the super passion into this scalar wave equation we obtained a set of differential equations where A and B which are called the couple which are called the coupling equations.

So the coefficients of the coupling the equations are KS, KIJ which consists of all the parameters of the structure like the spacing between the wave guides then the waveguide design and the refractive index contrast the operating wavelength and so on so forth so in particular the spacing this is a very sensitive element so as you increase the spacing with the coupling reduces and more and more length is need to couple the waveguides, so one of the important theorems that is applied here is called the orthogonality of modes of the wave guides.

Strictly speaking the orthogonality is not really applicable if the modes do not belong to the same wave guide but still we have taken a approximation to apply it and see that the couple mode equations are in very simple form.

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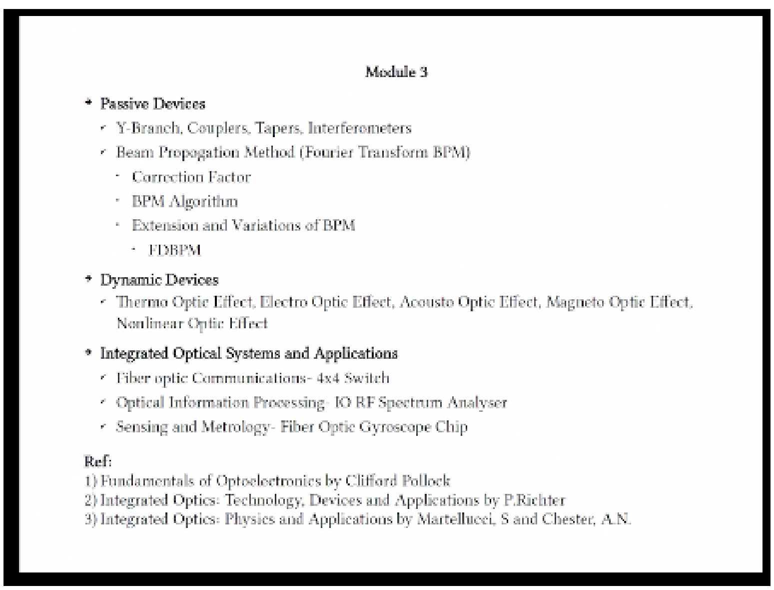

So then we looked at what are called the passive voice where you do not have any control on the operation but expect for the design we can design passive wave guide based on the technology and particular the lithography that is available and you can pattern the devices in whatever shape we want in particular way I have looked at braches couplers tappers and framers so on and so forth, one of the important feature in all this devices is the variation of refractive along the propagation direction that is z is the direction of propagation we have refractive index and there a function of z.,

So strictly speaking we cannot talk about the modes of a these devices but we have taken a approach where you can think of normal modes at any given cross section we can assume the device to be uniformly extend and consider the mode of that particular straight wave guide and use that mode to analysis this properties in particular we have motioned that we can divide the device along the propagation direction into several small segments and in the each segment we can find out the local normal mode and the study the each of these segments.

So this needs to what is called the beam propagation method where we have two steps rather two major steps where in the first step we take the Fourier transform of the input bream which gives the spectrum of various components of the input beam and then in second or second phase we apply correction factor so that the feel so that the refractive index variation is in cooperate into to that so there are vanities of beam propagation set in practice and we have motioned what is called Fourier transform BPM.

They were the spectrum of the input beam is used and each component is propagated separately at so one the cracks of the beam propagation method lies in finding out what is the correction fact, so by manipulating the wave equation and Maxwell's equations we can arrive at the correction factors in different forms the other important form that we have suggested is are most popularly used is called the finite difference become wave each of this variations or the derivatives are replaced with their difference formulas.

So it is form that the numerical methods are same numerical methods are very effective to solve such devices. Then we will look into dynamic devices where we use external effects like electro optic effect to study their properties so thermo optical effectively talks about variation of refractive index with application of heat the heat could be apply by using a electrodes and heating the waveguide.

And then the propagation constant can change due to this change in the refractive index and you can ever can called as thermo optic devices and we noted that there may not be very fast because of the slow nature of the thermal phenomena, so if you want to have a high speed devices one of the most popular techniques is called the electro optic effect where you will use applied fields and change the refractive index and properties of the material.

In particular we have showed that the lithium near bit is one of the most popular material which has got very high electro optical coefficient and so it has been a most popular material, so electro optic tensor of the lithium bit has got many, many components but we can choose appropriate component by choosing the direction of propagation of the light the orientation of the crystal and replacement of the electrodes and so on and so forth.

The highest electro optic effect can be obtained by using the coefficient R33 and which of course which has a implication on the amount of voltage that you had to apply to a obtain this field, so the electro optic coefficient is more we can have less voltage reapplied and so on. So one of the important features of electro optical effect is it could be very high speed we can consider the electrodes as coplanar or striplings and high frequency RFR microwave signal can be considered as propagating on these electrodes and creating a travelling wave and which can affect the light propagation in the optical waveguides.

So there is a microwave coplanar sip line microwave waveguide on top as there is some electrodes and optical wave in the waveguide. So the propagation can be studied and of course the electro optic effect in all these effects results in the refractive index which are variable with propagation direction and the similar techniques that we have mentioned in the previous chapter can be applied that numerical methods can be used to study these properties.

So electro optic effect could be used to make many other devices like optical switches for example we can take a directional coupler switch and then apply the voltage to make it into a bar state so you can switch between the cross over and bar state by using this electro optic effect and also we noted down later on that we can have higher order in devices by cascading these devices, so acoustic effect is one of the important techniques to create gratings.

So a travelling wave grating could be created on the substrate which could affect the light propagation characteristics by incorporating the wave guide in just below the travelling acoustic and so the grating, so all the gratings are one of the important elements in optical engineering they can be used for input output couplers we can use them acoustic optical effect for doing lot of optical signal processing we can have signal some of them could be attached to the electrodes IDT electrodes.

Some of the signals could be associated as a modulating signals to the light wave and so on and we can find out many, many properties of interactions of the light waves and acoustic waves are the RF frequencies is in the acoustic optic effect. Neither optical effect will implies you apply magnetic fields switch in the refractive index and other polarization properties of the medium and we can make important devices like polarizer's analyzer and so on.

So this parse magnetic fields and there are several application, so non linear integral optic effectively implies using the intensity of the light or the electric field of the light wave itself to change the properties which in the simpler terms it translates down to the power dependent refractive index if the refractive index is dependent on the input power then it has got different properties at different input powers and so with the hell lot of non linear effects.

In the bulk non linear optics we have many, many phenomena like second harmonic generation then the four wave mixing and so on and so forth which could be translated into integrated form the advantages that we can obtain these effects set much lower power than what we observe in the bulk optics so that is one of the important features of no linear integral optics which was not taken much detailed in this module.

So then we will look at some optical systems of applications of all these devices that we have studied and also some applications. So in particular we have looked at example of a fiber optic communication system we can make a 4/4 optical which by using five dasial couplers which has by configuring these directional couplers which has we get many, many connectivity options, we can represent that in the form of a matrix, almost all many combinations are possible but of course not all combinations which could be extended by going for higher number of optical which has in configuring in a different way is none of the direct applications acoustic be practice.

So then we have noted another important application of optic effective in the form of spectrum on the laser, so a typical spectrum analyzer will consists of acoustic optic cell or the IDD pattern which will create a grating on the chip and noted that integrated optical lenses are used for focusing defocusing where the functioning can be analogous to the rough bulk lenses, so I have not considered the integrated optical lenses in this particular course and with respect or from the references given at the end you can look at the properties and say what are the difference between the lenses in bulk and integrated.

So these RF spectrum laser we have RH field applied to the IDD pattern and optical films propagating through this planar waveguides and the gratings is created by this RF field the grating properties could be changed with the input RF fields suppose if the RF field id very some containing a broader spectrum all the components result in grating you can say that there is a super position of all these gratings the result in a particular refractive index variation pattern.

So the resulting output optical field could be considered as in effect of all these super position gratings and you can calibrate the output field such that it corresponds to what is truly presenting the RF spectrum. Similarly we can also reconfigure this as optical spectrum analyzer where we give the input signal to the light wave and RF frequency id fixed creating a fixed grating. Then we will look that example of integrated of a chip for application to fiber optic gyroscope.

Even though the gyroscope is not a device on the chip we can say that all the components necessary for the fiber optic gyroscope can be made on to the same chip, and it could reduce the size, weight and it is also possible to improve the sensitivity of the device because of this small nature of all these components and lower losses compared to the all fiber gyroscope and so on. So it is also possible to create devices for many, many applications like metrology.

For example, if you have an area of fiber brag gratings and the signal coming from differential and it should be analyzed it is possible to analyze by using these integrated optical techniques by creating gratings and other components on the same chip.

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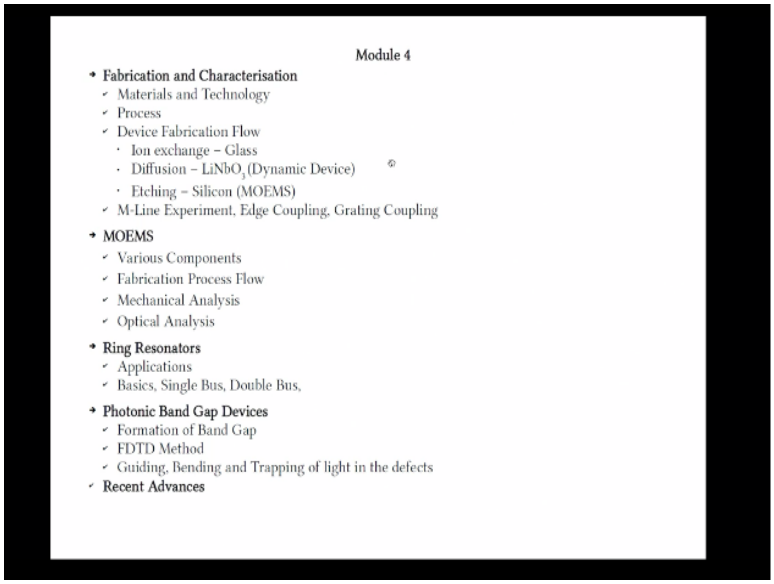

Then finally we will get some technological issues the module 4 starting with the fabrication and measurement of the properties of the optical waveguides and devices, so we start with the materials we said that there are lot of materials that are possible unlike in the electronics technology there are several materials that are being exploit right now, and like crystals, classes more importantly the silicon is one of the work courses of the presently electronics syndromes technology so that is also important option to consider for integrated optics applications.

So we lift up various processes that available for fabricating these under in different material systems like for example we saw that in class one of the common methods is call the receiver ionic change process then only lithium bit you can diffuse titanium and we change that for at next properties and also on silicon one of the most common techniques is lithographic patterning of the silicon layer by using the etching and it is also possible to combine this optical waveguides with main structures to create many other important properties.

One experiment we have discussed on the measurements it is a planar waveguide measurement is very important to characterize the process where we can estimate the diffractive index profile then the loss has and many other factors of the planar waveguides. So when it comes to the channel waveguide you can couple it by using the edge coupling through a fiber and also more recently the most popular techniques to couple light into the optical circuits is by grating couplers.

So then we will look at some more recent topics in particular the first one is the optical memes or MOEMS micro up to electro mechanical systems so the where you have looked at various components that can be possible on memes, there are two broad requirements here one is the mechanical components and then the optical components of course a lot of electrons which could be also integrated on to the silicon memes structures.

So we can associate these mechanical properties with the optical properties of the device we can say that the device optical properties could be controlled by the mechanical properties and for example the stressing dues that the base of the cantilever beam could be used control the light propagation optical waveguide or re-directional coupler where seen some examples like the pressure sensor and where the pressure on one of the arcs of the inter perimeter is effected by the mechanical structure.

So we will conduct the few process where you can fabricate this MOMES devices in particular we can us the two broad categories as bulk micro machining and surface micro machining these are the two broad line process that are use for MEMS optical MEMS applications. So we looked at a little bit of analysis on the mechanical side of the cantilever beam then the optical analysis which is similar to the propagation optical waveguides is considered.

So one of the important features of optical MEMS analysis and design this that is absorbed is the complicated several of the refract index profile die to the stress due to the mechanical subjects. So at this moment we said that numerical methods could be analyzed could be used analyze this phenomena, then another important recent development that we have taken up is called ring resonator in order to reduce a chip a utilization we thought ring resonates are important to components but in terms of the functionality also the have important properties in particular like the gratings they have frequency dependence.

So the resonate frequency is very, very sensitive function of the radius then the bus waveguide then the gap between the bus waveguide and the ring resonator and so on and so forth. So ring resonates we have found them to be having many applications in particular you can be used for optical communication filters and where we have see examples of a comb filter in this course where you have rings of different radii and then there is a common bus and there are bus waveguides to tap the output and we found that they provide a very sensitive function for different frequencies of operation.

We found we have some equations of their properties like the few factor then the free spectral range and so on and so forth, there are several configurations we looked at like a single bus ring resonator double bus ring resonator and so on and so forth. Finally we looked at photonic band gap devices also called photonic thistle based devises the formation of band gap is a important problem we said that the photonic band gap structure is a periodic refract index variation and due to that you have what is call the band gap only certain frequencies are allow to propagated band of frequencies are not allow to propagate that is why it is called the photonic band gap structure.

And the Band gap depends on many, many factors in particular the whole size there are two configurations we considered to holds in the sub state or rods on the sub state. So depending on the geometry crystal like structure and the refract index and many other properties we can determine and design this photonic band gap devices. One of the popular method we have considered is call the final different time domain method which we visited in the beginning of the course and which is one of the popular technique and we mention that there lot of rewired that can be used in particular the MIT photonic band gap tool as well as MPB these are several commercial ones which can be used to designing photonic band gap structure.

So this can be photonic band gap structure can be use for many applications like guiding make waveguides by making line defects you can make you may co resonator by creating point effects we can create line defects in the form of bends the form of tapers and so on and so forth we can also using the resonators we can apply to many, many other cases. So finally we have mention the several other important emerging trends in particular which we have not consider in this course or the photonic integrate circuits on active bacteria’s like gallium arsenide and in indium phosphide and so on and so forth.

This important feature because these are the materials which are commonly used for optical engineering applications and more importantly you can make lasers and other active device on the, this active sub states. So that is importance of using compound semi conductor devices then the other important recent advance in terms of the applications that we have mention are the quantum communications.

Quantum communication is one of the domain where we use properties quantum properties of the objects like electrons and photons, so in particular the polarization state of a photon is not well define if you take a single photon in the classical essence we have horizontal in vertical polarize of light well defined if you have continuous light wave. Whereas if you have talking about the photons in isolator photons their properties are not well determined they are determined by quantum mechanics and quantum optics.

And in a specific case we mention that the state of a photon is not well defined but as a super position of wave state which can be use for quantum communication applications. So in effect we can say that photons is one of the right ways to apply for quantum communication and quantum computing applications hopefully we will be able to take up that in some other course thank you very much for taking of this photonic integrates circuits course and all the best there are several differences I have given at the end which can be use to study further. Thank you once again.

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