Advanced Optical Communications

Prof. R. K. Shevgaonkar
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Lecture No. # 26

Wavelength Division Multiplexed Systems

In the last lecture, we discuss the design of fiber optic link. So, if you look back, up till now what we have done in this course is just discuss the basic components, which are needed to establish a link between two points. Say, initially we discuss the medium which is the optical fiber; then we talked about the sources like LEDs and lasers. Then we talked about photo detectors; then we talked about optical receivers. So, these are the basic components which are required to establish a point to point communication link.

Today, we are going to discuss essentially the advancements, which have taken place in the fiber optic communication due to advancements in laser technology, the advancements in fiber technology. So, these things which we are going to discuss now onwards; these are what are called the modern advances, which have taken place in the area of fiber optic communication. And one of the major things, which have happened in these area is the development of a system, what is called the wavelength division multiplexed system or in short, it is called the WDM system.

Now, what is the origin of this WDM system? If you recall when we discuss the point to point communication link, and the sources which are used for this and the detectors, we found that the detectors and the sources, they have a bandwidth limitation. What that means is that these sources cannot be modulated beyond the certain frequency. If you go to today’s technology, it will be very difficult to modulate an optical source beyond about 10 gigabits per second and same thing on the receiver side; it will be very difficult to detect the signal, which has a data rate higher than 10 gigabits per second.

So, it then looks that due to the limitations of the electronics or the electro optic converters, which are going to be used on either side of the optical fiber, we will not be able to increase the data rate beyond about 10 gigabits per second. In the laboratories people are investigating the data rates of 40 gigabits per second; but these are still at the experimental stages. If you look at the deployment of the systems, these systems are essentially less than about 10 gigabits per second systems. Later on, we will also see that due to the non-linear effects which are present inside the optical fiber, it is difficult to increase the data rate beyond about 10 gigabits per second.

So, that means if we establish a optical communication link and use one transmitter and one receiver, then effectively we can use the bandwidth of about 10 gigabits or 10 gigahertz. Let us now compare this number with the bandwidth which the optical fiber has. Well, if you remember when we started discussion on optical fiber, we had suggested that this is the medium which has a much larger information carrying capacity. We had seen that the optical fiber has a very large bandwidth; because it has low loss optical windows and effectively if you could make use of that bandwidth, then one can stuff a huge amount of information on the optical fiber.

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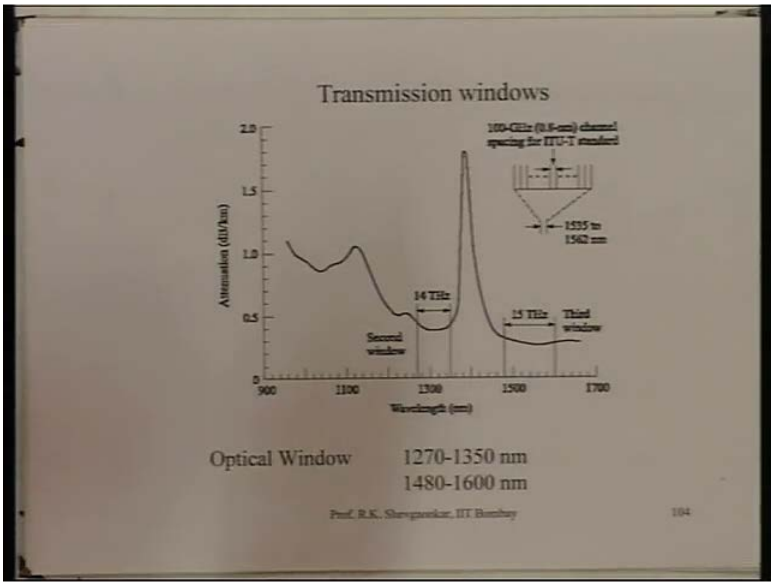

Transmission windows

Optical Window 1270-1350 nm
1480-1600 nm

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So, let us look at the low loss spectrum of the optical fiber what we call as the transmission window and this is the typical game profile or loss profile which you get for the optical fiber. Say, you have the wavelength going from about 900 nanometers to about 1700 nanometer and as we have seen earlier, there are two windows. The second window of optical communication, which is around 1300 nanometer and the other window is around 1550 nanometer; that is here the loss is low. Also now the advancement in the optical fiber technology has taken place, where even this peak is reduced significantly.

So, we have essentially a window which can extend (( )) about 1200 nanometer up to about 1600 nanometer, where loss is reasonably small. Even if we do not go in to reduction of this peak, we have the two windows; one around 1300 nanometer and (( )) around 1550 nanometer. So, if I see typically, this window would range from about 1270 nanometer to 1350 nanometer and this window would range from 1480 nanometer to about 1600 nanometer. If I convert this in to the corresponding frequency, typically we have a bandwidth here available which is about 15 terahertz and here about 15 terahertz. Say, total bandwidth which we have including these two windows is about 30 terahertz.

So, when we are having the medium which can support effectively a bandwidth of 30 terahertz; if we use only one transmitter and one receiver, we can use a bandwidth of only 100 gigahertz; that means we are off by factor of thousands in terms of utility of the optical fiber. Or in other words, if we use the optical fiber medium just for one channel transmission, then the system is highly underutilized and that is what essentially the origin of the WDM system. That can we do something now to exploit the bandwidth which intrinsically an optical fiber has? So, if you could make use of these bands effectively, we should be able to get effective bandwidth of about 30 terahertz.

Now, initially when the systems were designed, the systems were designed in 1310 nanometer window and you may recall that this was the window; because the dispersion was very low in this window. The material dispersion goes 0 around 1270 nanometer. So, the systems were developed around this window. Later on, as the system lens becomes longer and longer, evens this difference in the these two loss was significant and then the window was shifted to 1550 nanometer. So, this is the third generation system; this was the second generation system. Since initially the systems were already operating here and new systems started coming in to 1550.

For a while, we could use both this window; one channel of transmission in this window and one channel of transmission in this window. So, simultaneously on one optical fiber, two signals were transmitted; one in 1310 nanometer window; other one at 1550 nanometer window and both could carry the data rates typically of the order of few gigabits per second. So, essentially what we have done is we have multiplex now. What is called in wavelengths? So, we call this system as a wavelength division multiplexed system. So, we are all sharing the bandwidth which the optical fiber has and both the channels can carry independent information on two wavelengths.

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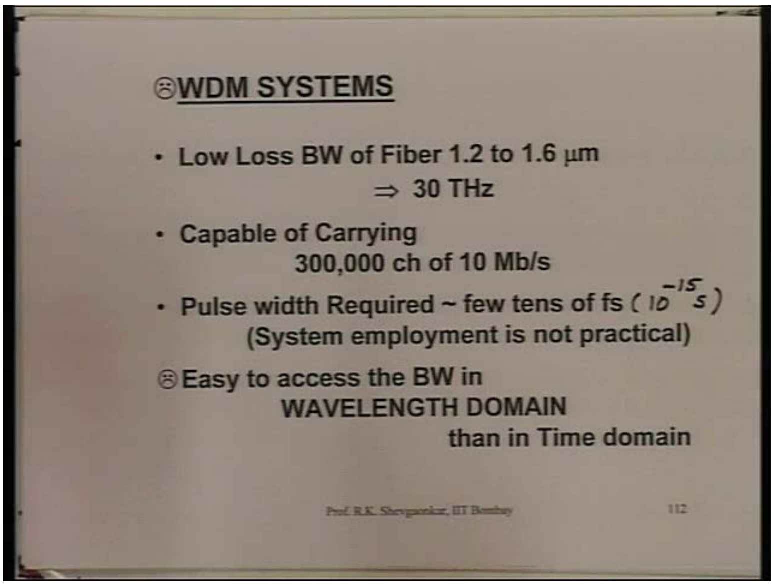

☹**WDM SYSTEMS**

- Low Loss BW of Fiber 1.2 to 1.6 μm
  ⇒ 30 THz
- Capable of Carrying
  300,000 ch of 10 Mb/s
- Pulse width Required ~ few tens of fs (10^{-15} s)
  (System employment is not practical)

☹Easy to access the BW in
WAVELENGTH DOMAIN
than in Time domain

Prof. R.K. Shevgaonkar, IIT Bombay 112

So, now if I look at the numbers what this essentially is telling you is that the low loss window of the optical fiber which is between 1.2 micron which is 1200 nanometer to 1.6 micron that is 1600 nanometer, we have a effective bandwidth of about 30 terahertz. If you want to talk in terms of the communication channels; that means this bandwidth can support effectively 300,000 channels of 10 megabits per second. I use the number 10 megabits per second; because if you want to have a video channel, that is the kind of bandwidth typically it would need for a good quality video. So, that means if we can use the entire bandwidth of the optical fiber, we would be able to transmit 300,000 video channels on a single optical fiber and that is a very huge capacity.

So, as we have been saying in this course that intrinsically the optic fiber is capable of supporting a huge amount of information and the limitation primarily is coming from the electronics, which is used on either side of this optical fiber. Now, to exploit this bandwidth which is 30 terahertz, there are two possibilities. Either we can exploit this bandwidth in time domain; that mean we can share this medium in time what is called the time division multiplexing. But in that case, then I would have generated the pulses which would be of duration typically inverse of this quantity. So, if I have 30 terahertz bandwidth utilization, then we require a pulse width which will be typically few tens of femtoseconds; femto is 10 to the power minus 15.

So, 10 to the power minus 15 second, which is extremely narrow pulse generation and especially with the semiconductor amplifiers, it will be extremely difficult to generate these kinds of pulses which are of duration 10 to the power minus 15 seconds. So, it immediately appears then that exploitation of this bandwidth of 30 terahertz is almost impossible in time domain; because we will not be able to generate the pulses which are as narrow as this. So, then the other possibility is that we should be able to use this bandwidth by dividing this bandwidth in to frequency bins and transmitting information independently in each bin and that is what essentially we do in what is called the wavelength division multiplexing.

That in this case, now we can access the bandwidth easily in the wavelength domain than time domain and this is far easier in terms of optical communication. Because as the laser technology has advanced, we can get now a very high quality laser at multiple wavelengths. Each wavelength can be modulated with different data rates and simultaneously multiple wavelengths can be transmitted on the same optical fiber. So, due to this characteristic that this large bandwidth cannot be accessed in time domain and the advancements which you have taken place in the laser technology; essentially the wavelength division multiplexed system came in to existence.

For a while, people were trying to see some other possibilities like using non-linear effects on optical fiber. Can we generate the systems? Can we go for coherent communication? But these options are far more difficult than simply transmitting multichannel signal on an optical fiber. In that sense, the WDM systems are far more realizable systems than any other options which are available. So, what we do in WDM system? Basically, we divide the signal in to multiple channels or we have multiple carriers in optical domain. Each carrier is modulated by data rate maximum possible data rate and all carriers simultaneously are transmitted on an optical fiber.

So, initially when the two windows were used, we had one channel transmitted in 1310 nanometer; other channel transmitted in 1550 nanometer and then we call this system as the WDM system, wavelength division multiplexed system. However as the time progressed and as I told that since the laser technology is now far more matured and its spectral width is significantly reduced, one can essentially put multiple channels even within a window of the optical fiber. And then since now the channels are closely packed, these systems are now called dense WDM system or DWDM systems.

So, dense wavelength division multiplexed system means within a band which is 1550 nanometer or 1310 nanometer, we have multiple carrier transmitted and then ITU has given certain standards for placing this wavelengths within the spectrum. So, what ITU is essentially specified is that within this window of 1550 nanometer, (Refer Slide Time: 04:36) we can put multiple channels. Each carrying the data rate or let us say 10 gigabits per second and these wavelength just to avoid the clashes and interferences. They have to be on a 6 grid what we call as the ITU grid.

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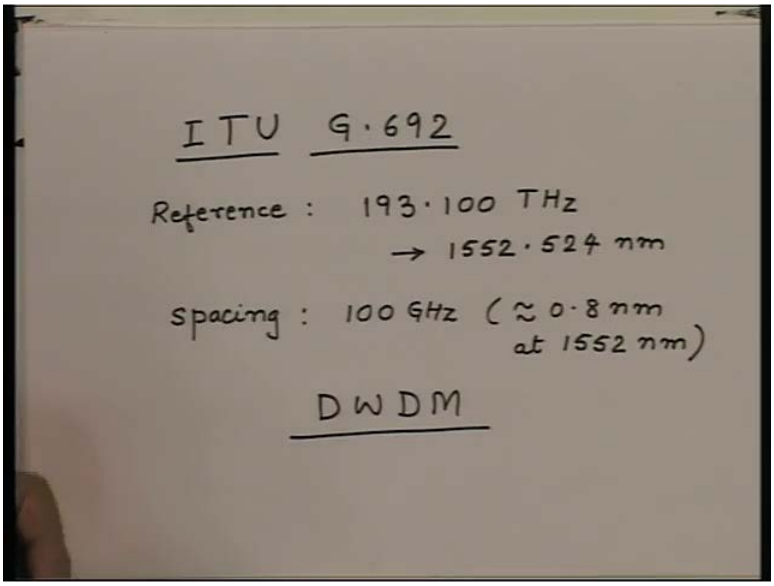

ITU G·692

Reference : 193·100 THz
→ 1552·524 nm

spacing : 100 GHz (≈ 0·8 nm
at 1552 nm)

DWDM

So, in a WDM system as per the ITU specification, we have ITU which is international telecommunication union. We have a standard which is G.692. Now for this standard, the reference frequency is taken as 193.100 terahertz. This corresponds to essentially a wavelength of 1552.524 nanometer and then the ITU specify that every 100 gigahertz, we can put another channel. So, the spacing which is specified for DWDM channel is 100 gigahertz, which is approximately, 0.8 nanometer at 1552 nanometer. So, the ITU grid is equi space in terms of frequency.

It is not equi space in terms of wavelength; because wavelength will depend upon the center wavelength here. The spacing will depend upon that. Say every 100 gigahertz, essentially we have a carrier and if we transmit the data of let us say 10 gigabits per second, the channel essentially will occupy about 2030 gigahertz bandwidth and then next channel which is separated by about 100 gigahertz. It will not overlap with the spectrum and we have a fair amount of isolation between different channels. So, this is the specification which we have for what is called the DWDM system, dense wavelength division multiplexed system.

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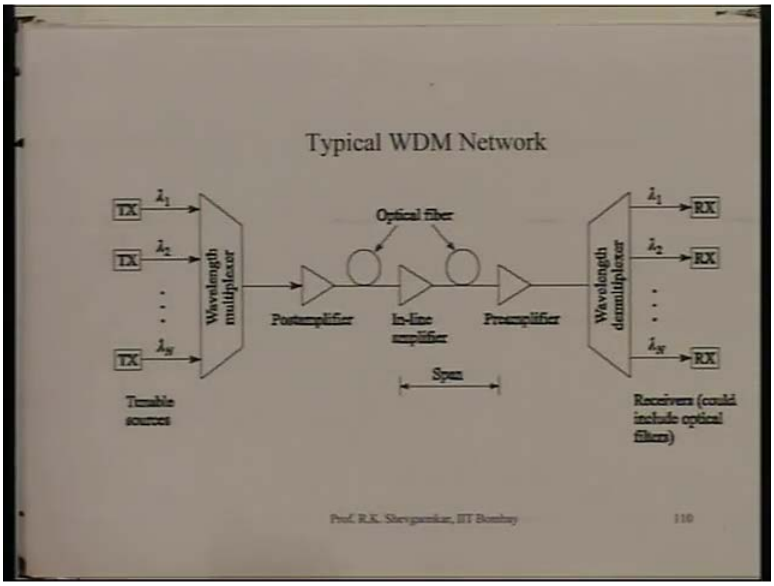
Typical WDM Network

Prof. R.K. Shevgaonkar, IIT Bombay 110

So, once you have this, then a typical WDM network would look something like this. We have a transmitter which operates at certain wavelength let us say lambda 1 and when I am saying a transmitter here, there may be a whole network behind this; that means the data multiplex from various locations are multiplexed and brought to this point here. This data now is riding on a wavelength lambda 1. Similarly, I can have a time division multiplexed data which comes from here and it is modulating a source lambda 2 and like that, we have a sources let us say there are n sources with different wavelengths lambda 1, lambda 2 up to lambda n.

Then we have a device here what is called the wavelength multiplexer or a power combiner, where all these wavelengths are essentially combined and you get one multiplexed output and this is given to the optical fiber. The system we are talking here still is point to point as far as the optical communication is concerned. You may have a complex network here. But the optical network which is this is still point to point. The whole multiplex data on different wavelengths is modulated and given to this optical fiber and the signal travels on this optical fiber link.

Depending upon the distance, you may require amplifiers periodic amplifiers. Because as you have seen earlier, when we were talking about the design of a communication link, that invariably the signal distortion is not very large. But the signal to noise ratio goes below the acceptable value. So, periodically you can put optical amplifiers. So, if the optical amplifier has a bandwidth larger than the bandwidth of altogether, then in one shot all these wavelengths can be amplified in the amplifier and the signal can keep propagating with periodic amplifications. It reaches on the other side, where we have a wavelength demultiplexer. So, the wavelengths are separated lambda 1, lambda 2 and so on.

And then you got your signal back which is time multiplexed data, which is sorted from here. So, this is the basic principle of the wavelength division multiplexed system that we have a complex time division multiplexed data. This data rides on different wavelengths and the different carriers simultaneously go on an optical fiber. On the other side, different wavelengths are demultiplexed. So, depending upon their destination, they will be separated and then again you can recover your time multiplexed data. So, what is the advantage if you go for DWDM system?

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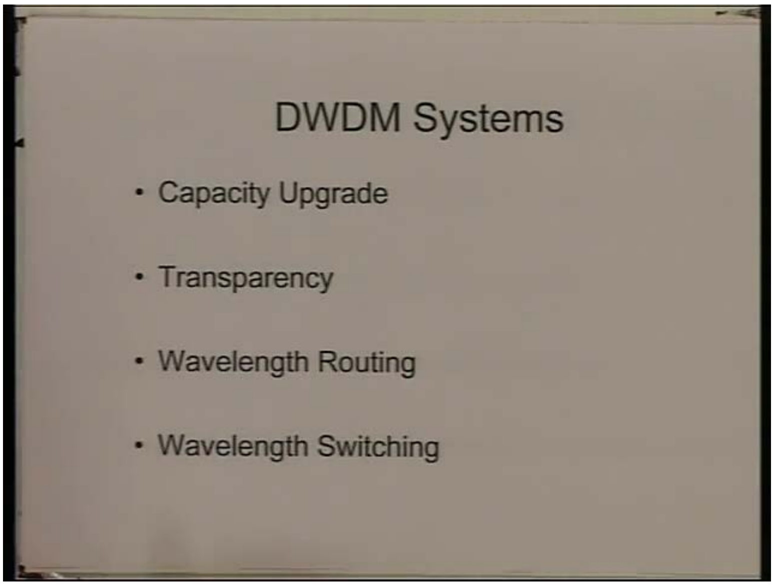

DWDM Systems

- Capacity Upgrade
- Transparency
- Wavelength Routing
- Wavelength Switching

The DWDM system is far superior compared to what you could get from the single channel. Firstly, it is very clear that we have a capacity upgradation and what do I mean by that is let us say today we have laid the optical fiber and we have got a requirement or let us say 10 gigabits per second. So, we can put one laser transmitter; but detect on the other side. We can send the information at 10 gigabits per second. Tomorrow, let us say our requirement increases to 20 gigabits per second; we do not have to change the link as such. Essentially, we have to add one more transmitter at another wavelength; just multiply these two wavelengths and send on the same optical fiber.

Our system capacity is doubled. So, just by adding more and more carriers, we can essentially upgrade the system to the desired requirement and the so very important characteristics of DWDM system that without significantly affecting the existing link, you can upgrade the capacity of the optical communication link. The second important aspect of WDM system is the transparency. Let us say if we had a data which was time division multiplexed. So, let us say initially we had a transmission of let us say 1 gigabit per second and now we upgrade our capacity let us say 2 gigabits per second in time division multiplexed system. So, the time slots are now reduced in size and also the data is now multiplexed in time.

So, one requires a precise information of a channel or a signal in the time frame. This demultiplexing is far more complex. So, when we upgrade now the data rates in a time division multiplexed system, the whole timing information has to be reallocate should be reworked out. Also if we go to the long links where there are repeaters in between, then for a time division multiplexed system essentially you have to demultiplex the data, amplify, clean, regenerate the data; again put on the optical converter. So, the whole process becomes very very complex; whereas, if we have a multiple carriers in optical domain, the formatting which is used for each of this carrier is irrelevant.

So, one carrier might carry some data rate in time domain; another carrier may carry some another data rate in time domain. And when we go to amplifiers are in between stations, a particular wavelength is amplified without worrying about what is carried by this wavelength. So, the whole information flow by using optical carriers becomes format independent and that is why, we call this as a transparency of the data formats. Because irrespective of what data format you are using, essentially the wavelength is the one which is deciding the characteristics of the signal flow now. The same thing can be extended now to what is called the wavelength routing.

So, earlier when certain information packet has to go to a certain destination in time domain, what one would do? One would just take the bits; read the bits; find out from that what the address for this packet and then route appropriately the packet. So, it requires essentially reading of the time bits. So, when a first data is coming in time division multiplexed system, you have to first of all demultiplex this data; read the bits; find outs its address, destination and then put back the packet; so that, it can reach to proper destination. When we go to the WDM system, essentially the wavelength itself can be used as an address.

So, all that information which we wanted to send to a particular destination, we can level it by wavelength let us say lambda 1. You have another information block you want to send to another destination, we can level it at lambda 2. So, now the whole routing of the information is just decided by the wavelength. So, without reading getting in to the bits and reading the addresses just whatever is coming on lambda 1 is routed to that particular destination; whatever comes from lambda 2 goes to another destinations and so on. And this is significantly now faster; because in time domain when we are reading the header of the packet, it requires some processing time.

So, wavelength routing would be much faster in optical domain; then going to time division multiplexed system. So, it gives you advantage that you can now route the wavelength by simply leveling the information by the wavelength. You can also switch the information from one wavelength to another wavelength. So, it is possible that when we talk about complex networks, we will see little later that information can go on a particular wavelength from one destination to another. But beyond that point, the information cannot go on the same wavelength.

So, either the wavelength can be blocked or you can transfer the information from one wavelength to another wavelength and the information can still keep flowing. So, wavelength division multiplexed systems have gone far beyond the simple point to point communication link, which we discussed here. (Refer Slide Time: 18:34) So, here we are simply combining the wavelengths and sending on the optical fiber to just to increase the capacity. But with the enhancement of technology advancements of technology, we have got now variety of devices in optical fiber which can do all these operations. It can do wavelength routing; it can do wavelength switching.

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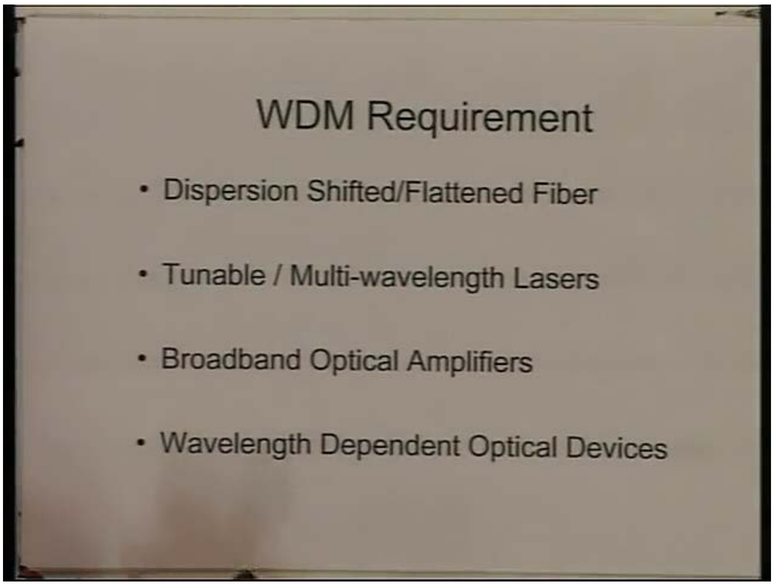

WDM Requirement

- Dispersion Shifted/Flattened Fiber
- Tunable / Multi-wavelength Lasers
- Broadband Optical Amplifiers
- Wavelength Dependent Optical Devices

So, then if we ask now what is the requirement of a WDM system? Firstly, since we are now going to put a large number of wavelengths in a window. The total wavelength division multiplexed signal will occupy a substantial bandwidth. If you are going to use a window which is 1550 nanometer, then we would require a fiber which has low dispersion in that window. If we have large number of wavelengths, then not only zero dispersion in that; but dispersion should be reasonably low over the entire wavelength range, which is used for WDM system. So, we require now as a backbone for WDM system; a dispersion shifted fiber for 1550 nanometer use or a dispersion flattened fiber, which can give you a very low dispersion over a very wide optical bandwidth.

We will also require the tunable or the multi-wavelength lasers; also switchable lasers. Because we can switch the information from one channel to another channel and today’s technology gives all this. But this is one of the important components, which will be required for WDM systems. Then we require broadband optical amplifiers; because its large number of channels is going to go on the optical fiber. The most efficient system would be if the amplification of all the channels together is done simultaneously. So, we are in search of the optical amplifiers which have large bandwidth and these are all become possible.

But they are again one of the important components for a WDM system and then we require a large number of wavelength dependent optical devices. For example, we may require a wavelength filter or we may require a wavelength dependent switch or we may require a wavelength dependent reflector. So, proper wavelengths are guided, routed, reflected; all those things can be done on specific wavelengths. So, essentially for a WDM network as a whole, we require large number of wavelength division dependent optical devices. So, component wise if I now look at what are the components which we require. So, what is the background technology which we need for a WDM system as a whole?

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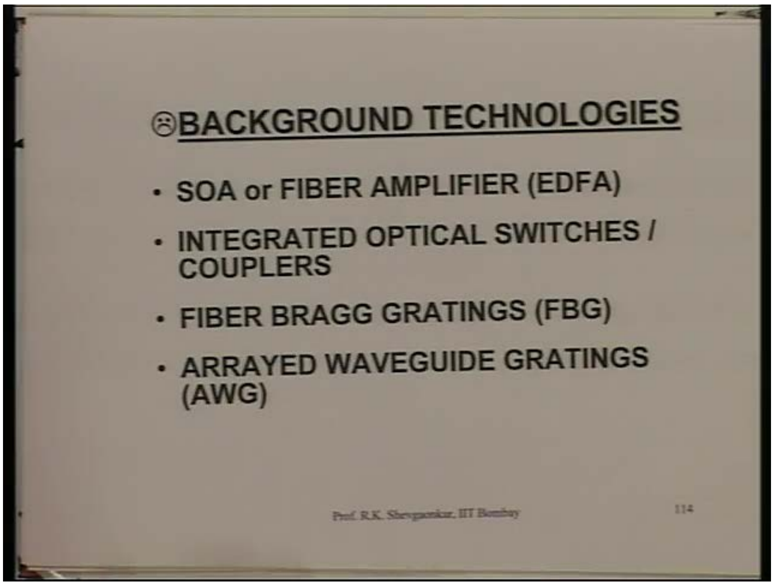

☹**BACKGROUND TECHNOLOGIES**

- SOA or FIBER AMPLIFIER (EDFA)
- INTEGRATED OPTICAL SWITCHES / COUPLERS
- FIBER BRAGG GRATINGS (FBG)
- ARRAYED WAVEGUIDE GRATINGS (AWG)

Prof. R.K. Shevgaonkar, IIT Bombay 114

So, we will require the amplifiers. So, the amplifier could be either semiconductor optical amplifiers or they could be fiber based amplifiers. And in that, we have EDFA erbium doped fiber amplifier. We will discuss all these things in detail or we can have now an amplifier what is called the Raman amplifier. Then the devices which are used like combiner of different optical channels. Dropping a particular wavelength or adding a particular wavelength and if you want to do this dynamically; that means you should be able to configure these things, we require devices what are called the integrated optical devices and in that, we can have integrated optical switches or couplers. So, in integrated optical device, essentially is IC version of an optical circuit.

So, if you create some kind of a optical guiding mechanism on a wafer; that will become a integrated optical circuit. Also we want to make the circuits on, the materials what are called the active materials; so that, their characteristics can be changed dynamically. So, integral optical devices is one of the key components that in modern optical communication systems. Then we have the devices which are based on fiber what are called the fiber bragg grating devices and these are extremely powerful devices in the sense that these devices are passive intrinsically and they are completely compatible with optical fiber. So, these devices can perform various functions of wavelength routing and switching and dropping by a miniaturized component, which is based on fiber. So, in recent years, the fiber bragg grating based devices have gained a wide popularity.

Then we have the devices what are called the arrayed waveguide gratings. These are essentially like a plane less structure which we have which can again perform the routing of the different wavelengths and so on. So, having understood now that for a WDM system these are the vital components; now, we look at each of this component in more detail. So, first we will try to understand the amplifiers. Then we will go to the integrated optical devices; then we will talk about Bragg gratings and then we talk about some other aspects of optical communication. So, these topics essentially would fall in a broad category of advances in optical communication. So, let us take now the first device which we need is the optical amplifier and let us go back to our original discussion of the fiber optic link design.

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Need for Optical Amplifier

- **Power Budget**

  Data rate 10Gbps

  BER 10^{-9}

  Tx Power 10dBm

  Min Rx power –45 dBm

  Fiber Loss 0.3 dB/Km

Repeater spacing ~ 200 Km

- **Rise Time Budget**

  Date rate 10Gbps

  DSF 1ps/Km/nm

  DFB laser 0.01nm

Repeater Spacing 3000Km

Let us do a simple calculation. You remember when we talked about the link design, we had two aspects. One was the loss in the optical fiber and other one was the pulse broadening on the optical fiber. The loss essentially is accounted for what is called the power budget calculation. Whereas, the broadening of the pulse which affect the data rate is essentially decided by what is called the rise time and so we have a rise time budget for the communication link. So, let us now take a typical numbers which we can use for an optical communication link and try to see the power budget and the rise time budget.

So, let us say we are transmitting the data rate of 10 gigabits per second; that is what I mentioned. We can go maximum to that rate and let us say we want to have a BER of 10 to the power minus 9. Let us say we have a transmitter power about 10 dBm and if you recall, this is already a very large power. Typically the power levels are about 0 dBm to plus 3 dBm and the minimum power required for this BER is about minus 45 dBm. So, if we take a fiber loss of 0.3 dB per kilometer, then because of power budget or because of the signal to noise ratio constraint, the repeater spacing has to be about 200 kilometer.

We can do the calculation for the rise time and we say that data rate is 10 gigabits per second. And if we use the dispersion shifted fiber, the dispersion on that could be let us say 1 picosecond per kilometer nanometer. And if we use a DFB laser, we can get the spectral width of the laser which is 0.01nanometer. So, we can get a repeater spacing which should be of the order of about few thousand kilometers. So, this calculation very clearly tells us that signal to noise ratio is the prime factor in deciding the location of the repeater. It also tells us that in the old systems wherever the repeaters were placed, at that location infact the signal to noise ratio was the one which has gone below the acceptable limit.

But signal has not distorted to really a very high value; that means distortion of the signal was acceptable. But since we did not have any option, we used to put a repeater there and we used to regenerate the signals. So, the signal to noise ratio is the problem at a distance of about 200 kilometer. Then there is no point in putting a whole regeneration system there; just a simple amplifier at this location would do. So, this calculation then essentially demonstrates that for long distance optical communication link, we do not have to put the repeaters over every 100 kilometer or 200 kilometer.

A simple optical amplifier can be placed at that location and the signal can be sent over few thousand kilometers without actually installing a repeater. And if you remember, we had mentioned that the repeater is a expensive proposition. So, if you could reuse the number of repeaters on the link and that is very desirable. So, this essentially makes now a case for an optical amplifier. So, we can send the signal over very long distances just by cascading the amplifiers and then these amplifiers are what are called the line amplifiers. What are the possibilities of amplification in optical domain?

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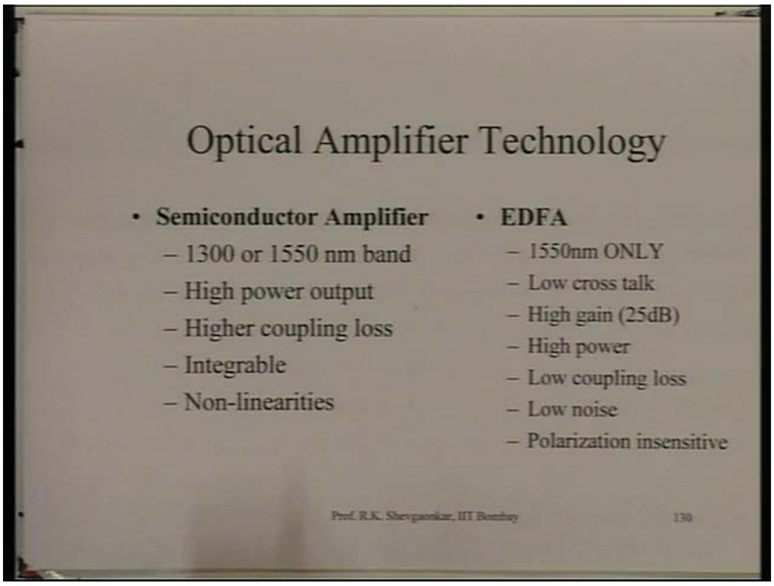

Optical Amplifier Technology

- **Semiconductor Amplifier**
  - 1300 or 1550 nm band
  - High power output
  - Higher coupling loss
  - Integrable
  - Non-linearities
- **EDFA**
  - 1550nm ONLY
  - Low cross talk
  - High gain (25dB)
  - High power
  - Low coupling loss
  - Low noise
  - Polarization insensitive

Prof. R.K. Shevgaonkar, IIT Bombay 130

We have two possibilities. One is the semiconductor amplifier semiconductor optical amplifier as we call it or it could be fiber based amplifier and that is the erbium doped fiber amplifier. Let us have a quick comparison of these two. The semiconductor of optical amplifier is nothing but a laser. If you recall, the laser intrinsically is an amplifier. By feedback, you can convert that in to a source. But intrinsically, laser is a device which can amplify the optical signals. So, infact all the thing which we have discussed for lasers that essentially can be used for creating an optical amplifier. And since we are now having sources which are in 1300 nanometer and 1550 nanometer, essentially we can create amplifiers in the same band.

The semiconductor amplifier can also give you high power outputs. But the biggest problem of semiconductor amplifiers is it has higher coupling loss. Signal is coming from the optical fiber; it has to be launched inside the semiconductor amplifier. After amplification, again the signal has to be coupled back in to the optical fiber and that gives you a significant loss. So, a semiconductor amplifier has a higher coupling loss from fiber to the amplifier and from amplifier to the fiber. This is integrable; because this is going to be a electronic semiconductor device and this amplifier also has non-linearities.

The other option which has become very popular which is the fiber based amplifier. An erbium doped fiber amplifier, this amplifier can only work in 1550 nanometer window. So, compared to semiconductor amplifier, which could be any of the windows. The EDFA works only in one of the windows, which is 1550 nanometer. But it has a large number of advantages. It has a fairly low cross talk; it can give high gain of about 25 to 30 dB; also it can handle high power; this is not very different than what this can do. But the biggest advantage of EDF is it is completely compatible with the optical fiber. Infact, this amplifier is built inside the optical fiber.

We will see later how this amplifier works. But basically is the same fiber if you dope with a material which is erbium, you can create an amplifier inside the optical fiber. So, it has a low coupling loss and that is a very desirable feature for an optical system. Also it gives very low noise and this is insensitive to polarization of the signal, which is amplified by this amplifier. So, EDFA essentially offers many more advantages over the conventional semiconductor optical amplifier and that is the reason, this amplifier has gained popularity over last one decade. Only limitation as we see for this amplifier is that it has to work only in the window, which is 1550 nanometer window. So, generically what is the amplifier characteristic?

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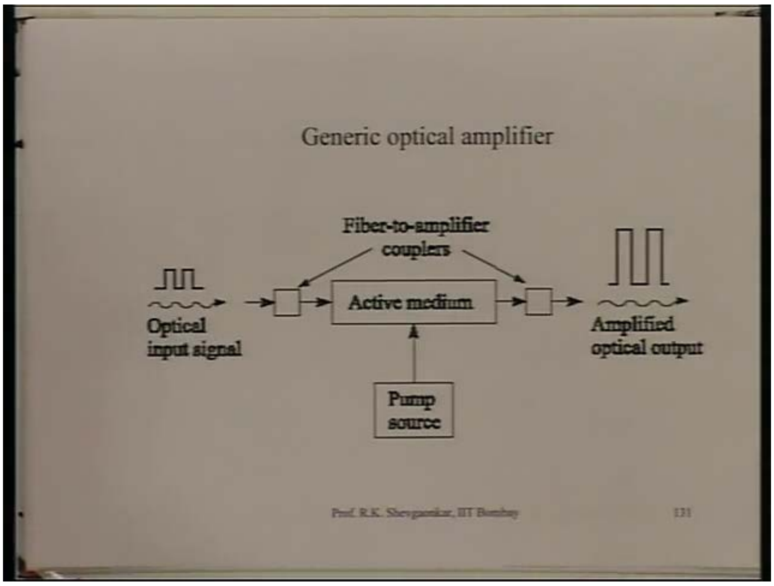

Generic optical amplifier

So, generically we know in an amplifier what we need is something called an active medium similar to what we have seen in laser. So what we do in laser? We have a medium which can be pumped. The material can be excited and then if the signal is incident on this, the stimulated emission would take place and the signal photons will get amplified in number. So, basically what we are looking for a intrinsically inside an optical amplifier is an active medium, a pump source which can excite this material and a coupling mechanism from the optical fiber to this active medium and vice versa. So, we have this optical input signal which is coming; it gets coupled to this active medium.

When it propagates inside this, the pump power gets transferred to the signal power and the signal comes out in the amplified form.

So, that is the basic requirement which you have inside an optical amplifier. So, in active medium, a pump source and coupling devices,which can couple the optical fiber to this device and back. So, essentially what we are looking for now a material first of all, which can have the energy levels corresponding to those wavelengths or frequencies which you want to amplify. So, we have seen a laser. Then if you are having the difference in the energy levels equal to the energy of the photon, then the stimulated emission can take place and the photon flux is amplified. So, firstly what we have to do is we have to identify the materials, which have proper energy level differences corresponding to the frequency of the signal, which you want to amplify and that is what essentially is done in this erbium doped fiber amplifier, EDFA.

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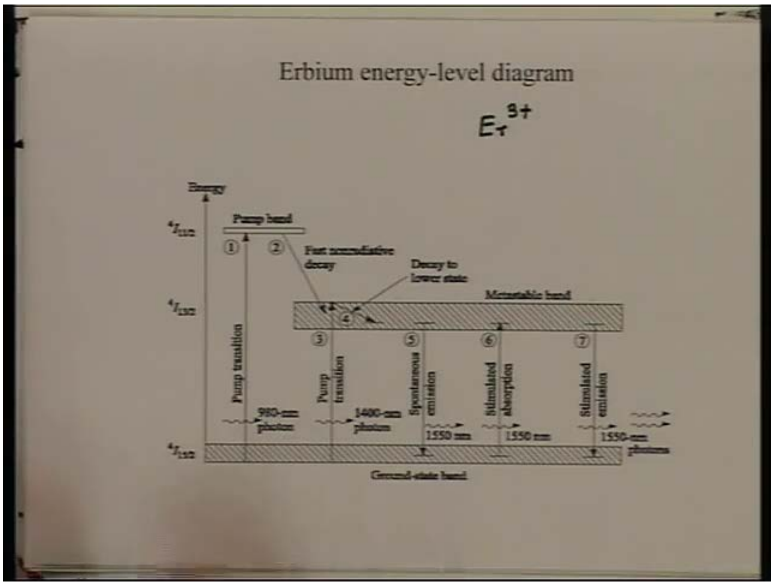

Erbium energy-level diagram

Er^{3+}

So, we have here the energy level diagram of erbium doped fiber amplifier. So, what is done we have the normal fiber glass fiber. The core of this fiber is doped with erbium atoms. So, we have a doping of erbium. So, it becomes an ion; so 3 electrons of this erbium atom are gone. So, that is why it is having a positively charged. So, if you take the glass and doped with this erbium ions, then we have the energy levels which will look something like this. So, as we have seen in terms of laser discussion, we have something called a ground state.

Then we have got excitation state and then we have got another state here which we call as the metastable state, where the electrons can come and wait. And then they can make a transition and they can give emission, which is to be stimulated. So, by putting the erbium, essentially we have created the energy level system inside the optical fiber and this difference between the metastable level and the ground level, this is in the range of 1550 nanometer. So, this is the difference of the energy we are going to make use of in the amplification of the optical signal in the window of 1550 nanometer.

Now, the idea here is as follows. We excite the atom from this level to this level and this difference corresponds to 980 nanometer. This difference from edge is 1480 nanometer to something like here which is about 1550 or 1560 nanometer. So, this band is fairly brought; it can go from about 1480 nanometer to 1560 nanometer and this band is difference is 980 nanometer. So, there are now two possibilities. One is we can pump this material with a 980 nanometer source; so is excited to this level first. Then the lifetime from this to this is very small of the order of about in some microsecond. So, very quickly the material relaxes to metastable level, which is this.

Then within this level, the system can relax to the lower energy levels which are more clustered here and then the stimulated emission can take place between the lower ends of this band to the ground state. So, since this band is very broad, there is a possibility that we can either pump material by transporting the electrons from this level to the higher end of this band, which is 1400 1480 nanometer. Or we can take the electrons to this level, which is 980 nanometer energy differences. So, erbium doped fiber amplifier can be pumped either by 980 pump source or by 1480 pump source. So, 980 pump source is more efficient; it can give you more gain; also it gives you less noise and so on.

So, 980 nanometer pumping is preferred compared to 1480 nanometer. Also since 1480 nanometer pump is close to the signal wavelength, the separation of the signal and the left over pump as we will see becomes more difficult. So, this is the basic material now we have identified, what is called the erbium doped glass, which has energy level such that the 1550 nanometer signal can be amplified. So, we will continue our discussion on this amplifier, which has really revolutionized long distance optical communication, because now by using this very tiny device erbium doped fiber amplifier, we can send the signals over hundreds and hundreds of kilometers.