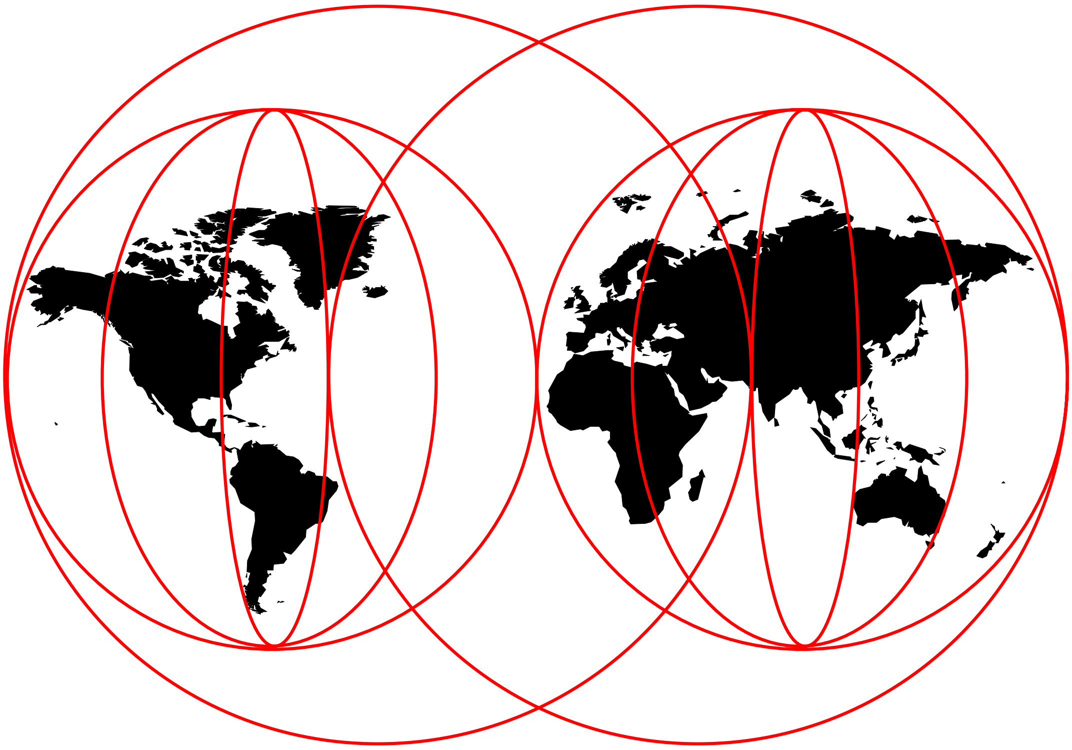
Understanding Optical Communications

Harry J. R. Dutton



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Understanding Optical Communications

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Take Note!

Before using this information and the product it supports, be sure to read the general information in Appendix F, “Special Notices” on page 591.

First Edition (September 1998)

This edition applies to fibre optic communications and optical networking.

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Other lasers use a cavity external to the device itself - these are called “external cavity lasers”. This allows a long cavity, and if you put a diffraction grating on one of the end mirrors you can get a very narrow linewidth indeed. (The record here is a linewidth of 10 MHz using a 20 cm (yes) long external cavity.)

Modes

In optics, a mode is a path that light may take through a system. Thus multimode fibre is fibre that allows for multiple paths. A multimode laser is one that allows multiple paths within its cavity and hence produces light of multiple wavelengths. Such lasers do not produce multiple wavelengths simultaneously with constant power. Rather, the laser will switch power from one mode to another very quickly (sometimes spending only a few picoseconds in any particular mode), apparently at random, when sending a single pulse. It is important to note that these are power level fluctuations not complete switching between modes. Thus the intensity of a particular mode may fluctuate by as much as 30 dB but it will not disappear altogether.

Thus the word “mode” relates to the path on which light is travelling at a particular instant in time. Light produced in a “multimode laser” is *not* “multimode light”. Light produced by a “multimode laser” travels in a single mode along a single-mode fibre perfectly well.

3.3.3 Fabry-Perot Lasers

The Fabry-Perot laser is conceptually just an LED with a pair of end mirrors. The mirrors are needed to create the right conditions for lasing to occur. In practice of course it is somewhat more complex than this - but not a lot. The Fabry-Perot laser gets its name (and its operational principle) from the fact that its cavity acts as a Fabry-Perot resonator (see 5.8.2, “Fabry-Perot Filter (Etalon)” on page 229).

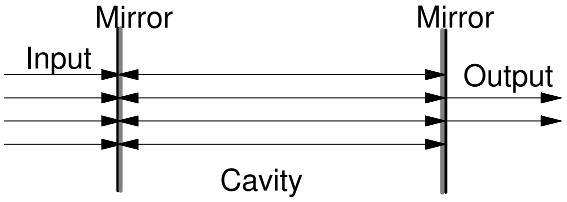

Figure 66. Fabry-Perot Filter. Light enters the cavity through a partially silvered mirror on the left and leaves it through a partially silvered mirror on the right. Only wavelengths that resonate within the cavity are able to pass through. Other wavelengths are strongly attenuated. This is described further in 5.8.2, “Fabry-Perot Filter (Etalon)” on page 229.

To understand the operation of the Fabry-Perot laser it is first necessary to understand the Fabry-Perot filter. The principle of the Fabry-Perot filter is illustrated in Figure 66. When you put two mirrors opposite one another they form a resonant cavity. Light will bounce between the two mirrors. When the distance between the mirrors is an integral multiple of half wavelengths, the light will reinforce itself. Wavelengths that are *not* resonant undergo destructive interference with themselves and are reflected away.

This principle also applies in the FP laser although the light is emitted within the cavity itself rather than arriving from outside.

In some sense every laser cavity is a Fabry-Perot cavity. But when the cavity is very long compared to the wavelength involved we get a very large number of resonant wavelengths all of which are very close together. So the important filtering characteristics of the Fabry-Perot cavity are lost.

We consider a laser to be “Fabry-Perot” when it has a relatively short cavity (in relation to the wavelength of the light produced). Wavelengths produced are related to the distance between the mirrors by the following formula:

$$Cl = \frac{\lambda x}{2n}$$

Where: λ = Wavelength
Cl = Length of the cavity
x = An arbitrary integer - 1, 2, 3, 4...
n = Refractive index of active medium

This is an extremely simple relationship. Notice here that the only other variable in the equation is the refractive index of the gain medium (dielectric) in the cavity. This is because we always quote the wavelength as what it would be if the wave was travelling in a vacuum.[51] Since the speed of propagation in the cavity is a lot lower than c (the speed of light) the wavelength is a lot shorter than it would be in free space. The adjustment factor is the refractive index.

In practice, we can't make the laser so short that we restrict it to only one wavelength. We need some space for stimulated emission to amplify the signal and we are limited by the density of the power we can deliver to a small area. Typically the cavity length is between 100 and 200 microns (of the order of 400 wavelengths or so) although devices with cavities as short as 30 microns have been made.

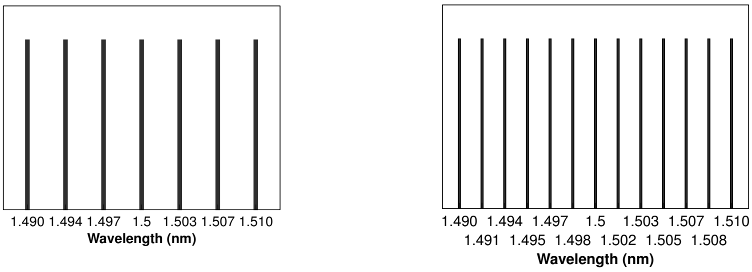

Figure 67. Resonance Examples

Figure 67 shows two examples of typical resonances. On the left we have solved the equation above for a cavity 100 microns long, a wavelength of 1500 nm and a refractive index of 3.45 (InP). We can see that there are 7 wavelengths within 10 nm of 1500 nm where resonance may occur. On the right of the figure we can see the same solution but for a cavity 200 microns long. Here there are 13 possible resonant wavelengths. The longer the cavity (and the shorter the wavelength) the more resonant wavelengths we can find within the vicinity of our centre wavelength.

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[51] A wavelength of 1500 nm in free space becomes a real physical distance of 1500/3.45 nm in InP which equals 434.78 nm.

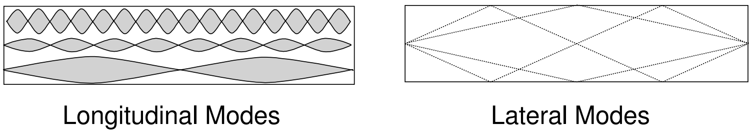

Figure 68. Resonance Modes in the Cavity of a Fabry-Perot Laser

Figure 68 (on the left) illustrates the principle of multiple resonant longitudinal modes in the FP cavity. We can get a number of resonant wavelengths provided the cavity length is an integer multiple of the particular wavelength.

On the right of the figure we see another problem. What if the *sides* of the cavity reflect light. What you get here are lateral modes forming which are also resonant and which can also lase! There are various ways of minimising or eliminating these lateral modes and this is discussed later. Transverse modes (vertical paths) cannot exist because the device is too thin in the vertical direction for multiple modes to exist. You could get a lateral mode that was completely side-to-side at right angles to the long axis of the device. You could also get a vertical one of the same kind. However, lateral modes are suppressed as discussed later and there is not enough gain in the vertical direction for lasing to be sustainable.

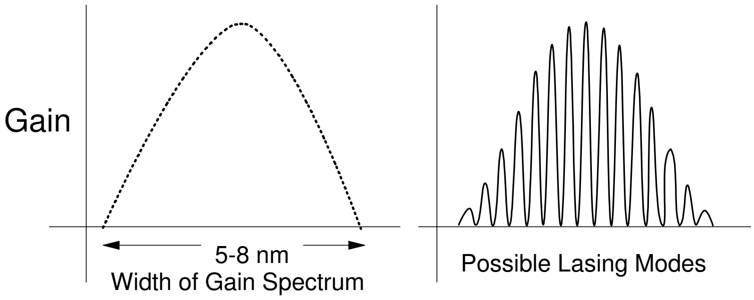

Figure 69. Modes Produced in a Typical Fabry-Perot Laser

The lasing medium can only amplify (undergo stimulated emission) over a fairly narrow range because of the characteristics of the material it is made from. A typical gain curve is illustrated on the left-hand side of Figure 69.

Width of Gain Spectrum

From the description of lasing in the previous section one could be excused for thinking that because there is a well defined energy gap between the higher and lower energy states there would only be one possible wavelength over which lasing could take place.

In fact the energy levels we have been discussing are rather “energy bands”. Electrons at a particular level have (slightly) different energies within the same band. So transitions from one band to another have some variation in energy (and hence wavelength) because electrons can leave from and arrive into slightly different energy levels within the same band. This varies a lot depending on the material constitution of the active region. Thus when you look at a pattern of spontaneous emission from the particular material you see a band of wavelengths with the strongest emission in the centre.

Of course during lasing, the amount of energy given up during the transition is *identical* to the energy of the stimulating photon.

When we combine the graph of possible resonant wavelengths with the amplifying characteristics of the device we get a pattern of possible modes like that shown on the right of the figure.

Thus an FP laser can produce a range of wavelengths. Each wavelength has to be able to resonate within the cavity and it must be within the gain window of the medium.

The laser output of each possible lasing mode is called a “line”. A simple gain guided FP laser produces a number of lines over a range of wavelengths called the “spectral width”. Because it is often difficult to determine just where the spectrum or just where an individual line starts or finishes it is usual to quote the width as a “Full Width Half Maximum” (FWHM). This is the point where the amplitude has decayed to half the maximum as shown in Figure 70. The linewidth of a laser is closely related to its coherence length; see Coherence Length and Coherence Time on page 100.

As will be seen in the remainder of this chapter, more complex lasers produce fewer lines (often just one). Also, more complex lasers are designed to produce very narrow lines. For most communications applications on SM fibre the fewer the number of lines and the narrower the linewidth the better.

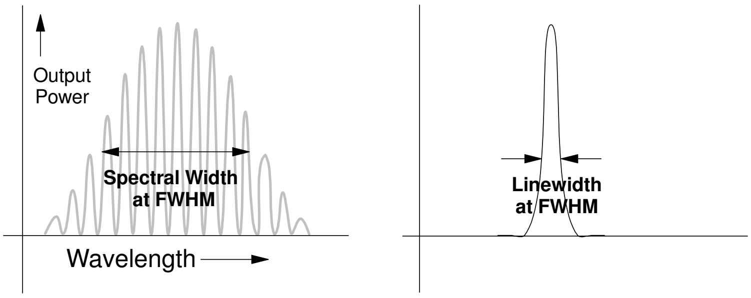

Figure 70. Spectral Width and Linewidth. These are usually measured as the width at half the maximum signal amplitude. That is at FWHM (Full Width Half Maximum).

3.3.3.1 Line Broadening

In the previous section it was noted that a single laser line consists of a narrow range of wavelengths rather than a single wavelength. This is due to the fact that rather than occupy a single energy state electrons may occupy a range of energy states within an energy band. Of course a given electron has an exact energy state at any point in time but a collection of electrons will have a range of (slightly) different energy states within the same band. The mean wavelength of a given transition is determined by the average energy level difference between the two bands involved in the transition.

Thus a laser transition produces a range of wavelengths over a (usually quite narrow) band. The gain curve produced has the typical bell shape of a "standard distribution". There are two mechanisms involved in causing electrons to have different energy states. These are referred to as "homogeneous line broadening" and "inhomogeneous line broadening".

Homogeneous Line Broadening

Sometimes called "natural broadening", this occurs when all of the electrons in the material have the same resonant frequency. Even though all of the atoms in the excited state are equivalent there are differences in energy level due to "uncertainty".

Inhomogeneous Line Broadening

Inhomogeneous Line Broadening takes place when the atoms in the medium have different resonance frequencies. This is the case with "Doppler Broadening" which is due to the thermal vibration of atoms. It is also the case when impurities are present in the material.

3.3.3.2 Laser Operation

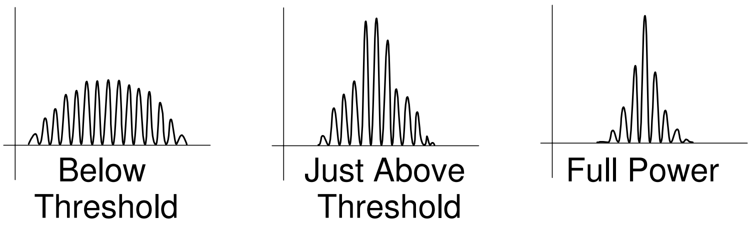

Figure 71. Output Spectrum Changes as Power is Applied. This figure illustrates a good quality Index-Guided FP laser. An unguided FP laser at full power produces as many as seven lines where a gain guided device typically produces three.

When power is applied to the device a number of interesting things occur:

Turn-on Delay

There is an inevitable delay between the time electrical power is applied and when the laser starts to produce coherent light. This is caused by the need to build up the carrier concentration in the cavity to the point of population inversion. The delay can be minimised by operating the device just below the "lasing threshold" (so that it fluoresces a bit in the OFF state). This means that there is already a carrier concentration present in the cavity and less power is needed to reach the inversion state.

Below Lasing Threshold

As the power applied to the device increases there is some fluorescence but lasing does not occur until the "lasing threshold" is reached. This is the power level where the amount of power applied just overcomes losses within the device. It is also the point at which a population inversion is achieved.

Just below the lasing threshold there are weak laser emissions at a range of wavelengths over the whole gain spectrum. This is caused by spontaneous emissions creating short lived laser action but the device has not got enough power for sustained lasing. This is shown in Figure 71 on page 106.

Just Above Threshold

Just above the threshold lasing gets stronger and (in good index-guided devices) there are only a few strong lines present. This is shown in the centre box of Figure 71 on page 106.

Operational Region (Full Power)

When power is further increased lasing begins to dominate emissions (spontaneous emission is almost eliminated). At this time a small number (in good quality index-guided lasers only one) of the lasing modes will dominate the lasing operation. Typically this will be the strongest mode. So the spectral width of the light produced will narrow substantially.

Hole Burning

After a very short time in operation lasing tends to use up the available excited electrons in the centre (dominant mode path) of the cavity. This happens because we often can't get power to all of the active region at an even rate. Thus a "hole" is burnt in the path taken by the dominant mode. The dominant mode is thereby significantly reduced in power.

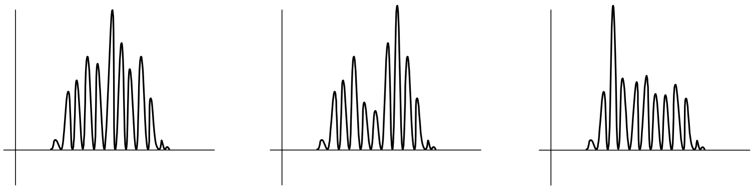

Figure 72. Typical Mode Hopping Behaviour in an Unguided FP Laser

Mode Hopping

Hole burning triggers mode hopping. When the strong, dominant mode decreases other modes are able to increase and become dominant.

Thus the laser produces light in one mode for a very short time and then it "hops" to another mode, and then to another and then to another. The whole range of resonant modes within the gain spectrum may be covered. This happens very quickly (a few tens of picoseconds per hop) so you get the effect of the laser producing a band of wavelengths.

It is important to note that when a single mode dominates the others are usually not suppressed entirely but they are strongly attenuated.

When the signal is sent on a dispersive medium mode hopping can become an additional source of noise. This is because each mode is at a different wavelength and each wavelength will travel at a different speed within the fibre. Not only will the pulse disperse but the dispersion will be irregular and random in nature.

Chirp

Immediately after power is applied to a laser there is an abrupt change in the carrier (electron and hole) flux density in the cavity caused by the lasing operation itself. This density of charge carriers is one factor that affects the refractive index. In addition, the temperature in the cavity increases quite rapidly. This temperature increase is too localised to affect the length of the cavity immediately but it does contribute to changing the refractive index of the material in the active region (within the cavity).

These changes in the RI of the cavity produce a rapid change in the centre wavelength of the signal produced. In the case of semiconductor lasers a “downward” chirp is produced. The wavelength shifts to a longer wavelength than it was immediately at the start of the pulse. It is not a large problem in short distance single-channel transmissions but in long distance applications and in WDM systems chirp can be a very serious problem. This is due to the fact that it broadens the spectral width of the signal and interacts with other aspects of the transmission system to produce distortion. Indeed, the chirp problem is the main reason that people use external modulators for transmission rates in excess of 1 Gbps.

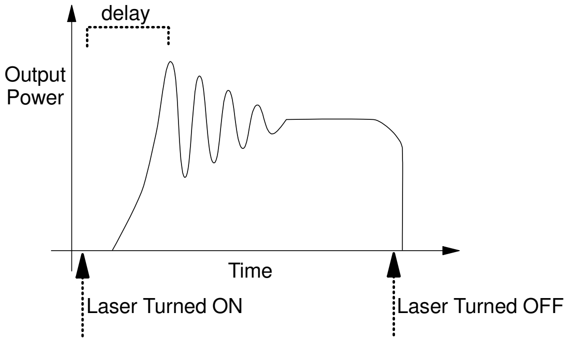

Figure 73. Relaxation Oscillations

Relaxation Oscillations (Ringing or Spiking)

When the laser is turned on you get short term fluctuations in the intensity of the light produced called “relaxation oscillations”.

When power is applied to the laser the upper energy state population builds up until an inversion occurs and lasing can commence. However, lasing can deplete the upper energy state very quickly and if pumping isn't quite fast enough lasing will momentarily stop. Very soon afterwards it will start again as the pump builds up a population inversion again.

This effect varies widely between types of laser. Some can turn on with little or no relaxation oscillation, others (if the pump is a little bit weak for example) can produce these oscillations interminably and never reach a stable lasing state.

Most semiconductor communications lasers produce some relaxation oscillation at the beginning of each pulse but stabilise quite quickly.

Relative Intensity Noise (RIN)

RIN refers to a random intensity fluctuation in the output of a laser. The primary cause here seems to be the random nature of spontaneous emissions. As the laser operates new spontaneous emissions occur and some of them can resonate within the cavity and are amplified. This causes some fluctuation in output power.

Phase Noise

The random changes in emissions described above under RIN are by nature different in phase from previous emissions. This causes random changes in phase during laser operation. This variation is a natural consequence of the way lasers operate and cannot be suppressed. However, the effect is not important in amplitude modulated systems.

Intercavity Noise

Intercavity noise is caused by reflections returning a portion of the optical signal back into the laser cavity. When a signal returns into the laser cavity due to a spurious reflection it is at exactly the right wavelength and will be amplified in the cavity. This causes unwanted fluctuations in the light output.

In general there are two kinds of noise here. The first is caused from nearby reflections such as from the laser-to-fibre coupling. This can be minimised by using anti-reflection coatings and lens couplings designed to minimise reflections. The second is caused by reflections from more distant optical components. In some systems (especially long distance systems) an optical isolator is used immediately following the laser to eliminate the problems caused by these far-end reflections.

Drift

After the device has been operating for a while the temperature of the device can change (it will heat up) and this will affect the cavity length and the wavelength will change. Also, there are effects caused by age of the device and the materials it is made from. Some of these effects can cause a slow change in the wavelength over time.

3.3.3.3 Construction of a Fabry-Perot Laser

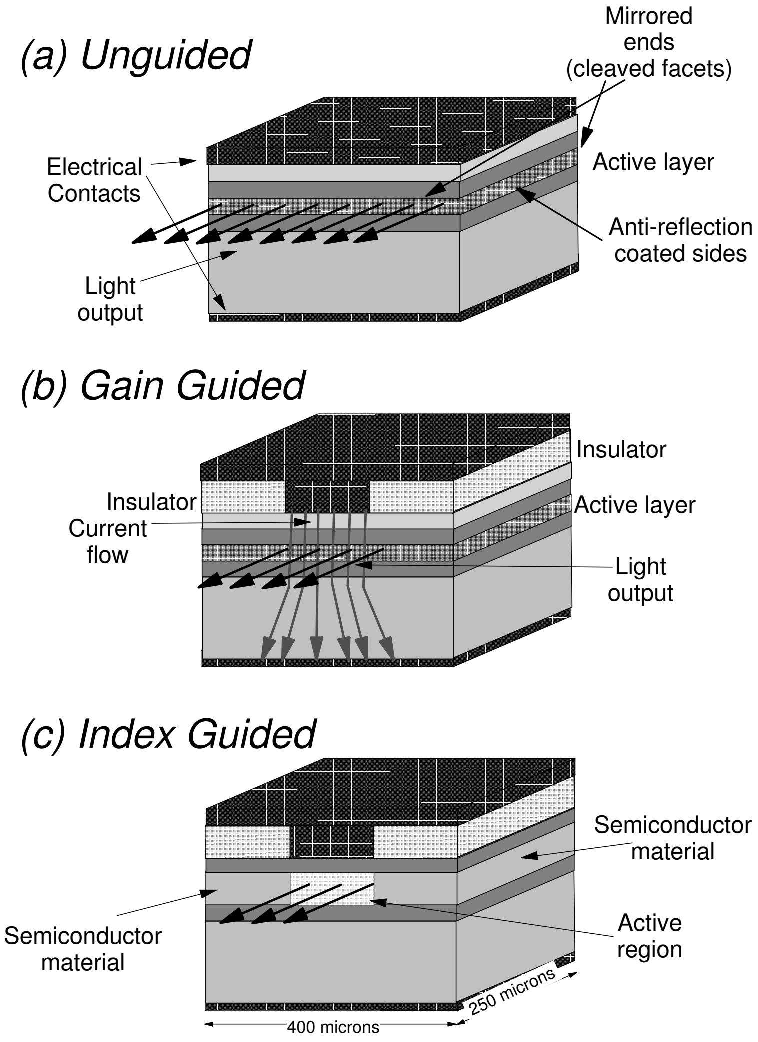

Figure 74. Directing the Light in a Fabry-Perot Laser

In its basic form an FP laser is just an edge-emitting LED with mirrors on the ends of the cavity.

On the surface of it, an FP laser should be easier than an LED to construct. In an LED you have to give a lot of attention to collecting and guiding the light within the device towards the exit aperture. In an ideal laser you don't have the problem of guiding the light at all. Lasing takes place only between the mirrors and the light produced is exactly positioned. Unfortunately it isn't as simple as this.

A simple double heterostructure laser is shown in part (a) of Figure 77 on page 113. Mirrors are formed at the ends of the cavity by the "cleaved facets" of the crystal from which it is made.

> These devices are made from a *single* semiconductor crystal and the planes of the crystal are exactly parallel. When the device is constructed it is not "cut up" but rather cleaved (cracked) along the planes of the crystal. This results in exactly parallel mirrors at each end of the cavity. The interface of the

semiconductor medium (refractive index usually around 3.5) and air (RI around 1.1) forms a mirror.

The active layer is very thin and the refractive index difference between the material of the active layer and the surrounding material is not great. Thus you don't get lasing in the vertical (transverse) mode. You can get lasing in the lateral mode but this is minimised by either coating the sides with an anti-reflection material or just making sure the sides are rough (cut rather than cleaved).

You do however get lasing in the longitudinal mode across the full width of the device. This is a problem as the device will tend to produce many different localised areas of lasing (at different wavelengths). A more significant problem is that it becomes very difficult to guide the light into a fibre! In answer to this problem two general techniques have been developed - Gain guidance and Index guidance.

3.3.3.4 Gain Guided Operation

In order to get lasing on a particular path we need the gain along that path (optical gain) to exceed the loss. We can get quite good control of device lasing if we control the entry of power (current in the form of electrons and holes) to the active region. Lasers using this principle are said to be "gain guided".

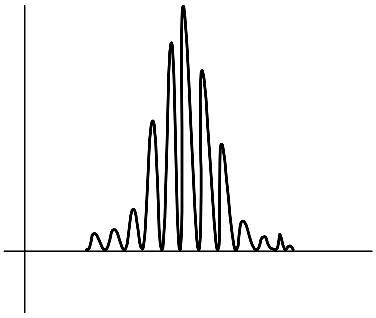

Figure 75. Emission Profile of a Gain-Guided Fabry-Perot Laser. Note the asymmetry of the line structure. This is caused by Raman Scattering effects within the cavity.

The typical technique used to guide power into the active region is to limit the area of electrical contact on the surface of the device. In part (b) of Figure 74 on page 110 we see that power is applied along a stripe on the top of the device (in this example). Current will flow predominantly along the path of least resistance (the shortest path) as shown by the grey arrows.

When this happens power is delivered into the active layer in a long stripe. There will easily be sufficient gain along this path (longitudinal mode) for lasing to occur but transverse modes and longitudinal modes outside the region of power delivery may not have sufficient gain to sustain lasing. Thus we get a narrow beam of light issuing from the centre of the active region.

Gain guided FP lasers produce a spectral width of between 5 nm and 8 nm consisting of between 8 and 20 or so lines. Linewidth is typically around .005 nm.

3.3.3.5 Index Guided Operation

Gain guidance can be further improved if we put stripes of semiconductor material (with a high bandgap energy) beside the active region. So we now no longer have a flat layer of active material throughout the whole device but just a narrow stripe through the middle. This is called a “buried heterostructure”. Since the active region is now bounded on all sides by material of a lower refractive index (generally about .1 lower) mirrored surfaces are formed and this serves to guide the light much better than gain guidance alone.

An interesting variation on this technique is to use a *lower* RI in the active region than the material surrounding it. In this situation any light that strikes the edges of the cavity is captured and guided OUT of the cavity. Additional modes reflecting from the walls of the cavity are thus eliminated. This is not too much of a power loss since lasing cannot occur in these modes and only spontaneous emissions will leave the cavity by this route. However, while this is an interesting technique the bulk of commercial devices use the former technique of a higher RI within the cavity.

Index guided FP lasers produce a spectral width of between 1 nm and 3 nm with usually between 1 and 5 lines. Linewidth is generally around .001 nm. (Much better than the gain guided case.)

3.3.3.6 Modulating the Signal

The simplest and most common way of introducing modulation into the light beam is simply to modulate the drive current of the laser. There are many forms of external modulators available and these are discussed in 5.9, “Modulators and Switches” on page 238.

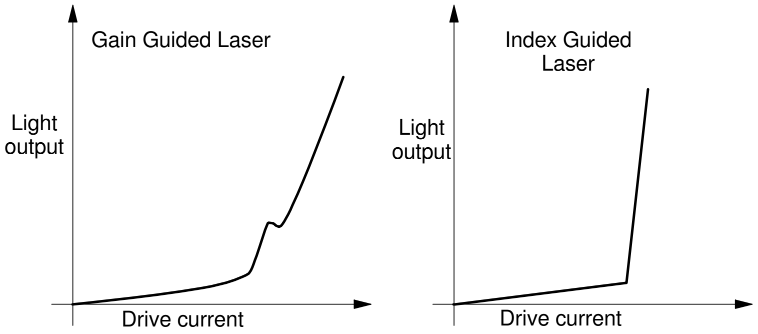

Figure 76. Fabry-Perot laser Output versus Input Current

Figure 76 shows how laser output varies with current input. The kink in both curves is the “lasing threshold” where lasing begins. Notice that the non-linearity of the curve for the gain-guided case makes this kind of laser useless for analogue modulation. However, it will modulate satisfactorily with digital OOK (On-Off Keying).

Operational Characteristics

> For digital modulation it is usual to operate the laser such that a zero bit is represented by a voltage (reflecting a current) at or just above the lasing threshold. This helps the device respond to high frequency modulation. It also means that there is some light output in the zero state. A ones state is usually set at just below the maximum output level.

Extinction Ratio

The extinction ratio is the ratio between the light output at full power and light output when a zero bit is being signaled. As mentioned above this is usually above zero. Extinction ratio is a measure of the difference in signal levels between a one and a zero state. It is usually quoted in decibels (dB).

Temperature Control

For most communications lasers temperature control is critical. The curves shown in the figure above shift significantly to the right as temperature increases. This changes the lasing threshold and the voltage levels needed to operate the device. Some of the lower cost devices can be satisfactorily operated with just good heat sinking. However, most lasers intended for long distance telecommunication applications are packaged with thermoelectric coolers and thermostatic Control.

Power control

One way of ensuring consistent operation over time (and perhaps saving the cost of cooling) is to monitor the light level produced by the laser and to adjust bias currents accordingly. This is often done by using a monitor diode at the back facet of the laser. Provided the back facet lets some light out (it usually does) you can measure the output power produced and control the laser accordingly.

3.3.4 Distributed Feedback (DFB) Lasers

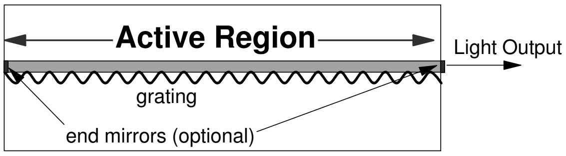

Figure 77. DFB Laser - Schematic

When we want to use lasers for long distance communication we find that standard FP lasers have significant problems:

1. As seen above FP lasers produce many wavelengths over a spectral width of between 5 and 8 nm. Even if we are using the 1310 “zero dispersion” band or “dispersion shifted” fibre in the 1550 nm band there will still be some chromatic dispersion of the signal caused by dispersion being slightly different at the different wavelengths.
2. The “mode hopping” behavior of FP lasers gives rise to “Mode Partition Noise” as described in 2.4.3, “Mode Partition Noise” on page 67.
3. In Wavelength Division Multiplexed (WDM) systems we want to carry many multiplexed optical signals on the same fibre. To do this it is important for each signal to have as narrow a spectral width as possible and to be as stable as possible. Regular FP lasers have too great a spectral width for use in this application.

Distributed FeedBack (DFB) lasers are one answer to this problem. The idea is that you put a Bragg grating into the laser cavity of an index-guided FP laser. This

Nominal Wavelength

The wavelength of the filter that was intended by the manufacturer. This is usually printed on the outside of the device. The real centre wavelength is sometimes different.

Bandwidth

It is easy to see from the shape of the right-hand filter that the bandwidth of the filter is going to depend a lot on just where you measure it. Bandwidth is the distance between the filter edges (in nm) at a particular designated distance below the peak. This distance is always quoted in dB. It is common to talk about the 1 dB bandwidth the 3 dB bandwidth or even the 30 dB bandwidth.

Polarisation is also an important factor here. Both the centre wavelength and the bandwidth are often polarisation dependent although these characteristics are usually quoted assuming unpolarised light. Sometimes the centre wavelength and the bandwidth are quoted as maxima and minima indicating the range of variation possible with changing polarisations.

5.8.2 Fabry-Perot Filter (Etalon)

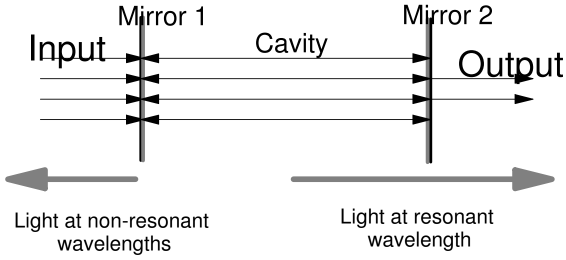

Figure 191. Fabry-Perot Filter

One of the simplest filters in principle is based on the Fabry-Perot interferometer. It consists of a cavity bounded on each end by a partially-silvered mirror. If the mirrors can be moved in relation to each other the device is called an “interferometer”. If the mirrors are fixed in relation to each other (such as with spacers) then it is called an “Etalon”.[77]

> *In principle this is just the same as almost every musical wind instrument (organ, flute, oboe...).*[78] *When we excite the air column within a wind instrument, the column resonates at a frequency (wavelength) determined by the length of the air column and the speed of sound in the air within the column. Wavelengths produced are such that an integral number of half-wavelengths must fit exactly within the column. Other factors such as whether the ends of the column are open or closed complicate the analogy so we will take it no further.*

Operation is as follows:

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[77] This is really an optical version of the electronic “tapped delay line”, “transversal” filter or Standing Acoustic Wave (SAW) filter. In the digital signal processing world the process is performed with a shift register.

[78] Most other instruments too but the analogy isn't quite so clear as it is with wind instruments.

- Light is directed onto the outside of one of the mirrors.
- Most is reflected and some enters the cavity.
- When it reaches the opposite mirror some (small proportion) passes out but most is reflected back.
- At the opposite mirror the same process repeats.
- This continues to happen with new light entering the cavity at the same rate as light leaves it.

If you arrange the cavity to be exactly the right size, interference patterns develop which cause unwanted wavelengths to undergo destructive interference. Only one wavelength (or narrow band) passes out and all others are strongly attenuated.

This is a very interesting process and is just a generalisation of the earlier example of light passing through a sheet of glass in 2.1.3.2, “Transmission through a Sheet of Glass” on page 22. The interesting effects occur on the mirror at *entry* to the cavity:

- When light of a non-resonant wavelength reaches the mirror most of it (depending on the mirror's reflectance) will be reflected. The small amount that gets through into the cavity will bounce around for a while but will ultimately exit through one of the end mirrors or be absorbed by losses.
- When light of the resonant wavelength reaches the entry mirror it passes through into the cavity without loss! This is a very interesting effect.
  - Assuming there is already light of the correct wavelength resonating within the cavity a proportion (small) of this light will try to exit from the cavity (because the mirror is only partially reflective).
  - Arriving light that is at the resonant wavelength and coherent with that in the cavity will try to reflect (or most of it will).
  - However, there is destructive interference between light (of the resonant wavelength) leaving the cavity and light coherent with it reflecting from the entry mirror.
  - The result here is that 100% of the incident resonant wavelength light passes through the mirror and into the cavity!
  - In addition light of the resonant wavelength already inside the cavity cannot exit through this mirror (because of the destructive interference with incoming light). 100% of it is reflected and therefore it can only leave the cavity through the opposite mirror! (Or perhaps be absorbed by losses.)

  Thus light of only the resonant wavelength is accepted into the cavity without loss while all other wavelengths suffer significant reflection.

The most important requirement for the functioning of a Fabry-Perot filter is that the reflecting surfaces should be extremely flat (preferably within one hundredth of a wavelength) and absolutely parallel. And of course this is the biggest challenge in building them. It is usual to silver the glass surfaces so that each forms a 99% reflective mirror.

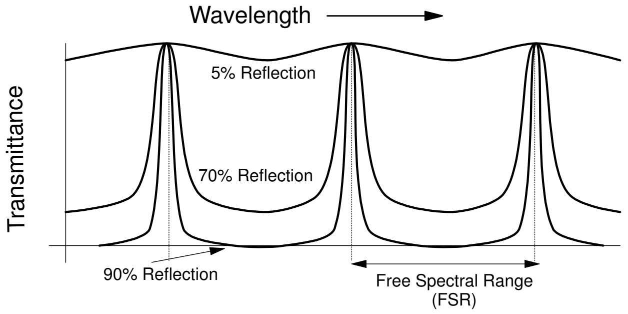

Figure 192. Fabry-Perot Filter Characteristics. Note the narrow passband when the mirror reflectance is relatively high.

The recognised measure of "goodness" of an FP filter is called the "Finesse". This is the ratio of the amount of energy stored within the filter to the amount of energy passing through it. It is much the same concept as the "Q" in electrical circuits. The higher the finesse the narrower the passband and the sharper the boundaries. The major factor influencing the finesse is the reflectivity of the mirrors - the more reflective the mirrors the higher the finesse. Absorption within the device and especially within the mirrors reduces the sharpness of the filter peaks.

This is illustrated in Figure 192. Notice that the three lines representing mirror reflectivities of 5%, 70% and 90% respectively all reach 100% transmission (through the filter) at the peak. The peaks are the resonant wavelengths (the lobes of the filter). The distance between the peaks is called the "Free Spectral Range" (FSR) of the FP filter.

$$FSR = \frac{\lambda^2}{2 \times n \times D}$$

Here, n equals the RI of the material between the mirrors and D equals the distance between them.

The finesse of the filter is the ratio of the distance between the transmission peaks (the free spectral range) to the width of each spectral line at the FWHM[79] point.

$$Finesse = \frac{FSR}{FWHM}$$

The resonant wavelengths are given by:

$$\lambda = \frac{2\,D\,n}{m}$$

Where m is an arbitrary integer 1, 2, 3...

If we have a device with an air gap (RI = 1) of 500 microns then the first order (m=1) resonant wavelength would be 1 mm which of course is not light but

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[79] Full Width Half Maximum

microwave. Looking at resonances in the wavebands of interest we find (with n = 645) lines at 1,552.8 nm, 1,550.39 nm, 1,547.99 nm etc.

An FP filter is inherently multi-lobed in the sense that it has multiple passbands but in practice only a single lobe is used. With the spacing between lines (FSR) of only around 2 nm this filter would not be very useful for recovering a signal from a WDM stream (say) 20 nm wide. To increase the FSR we must decrease the spacing between the mirrors.

Energy that is *not* passed through the filter interferes and is reflected back to the source. This must be considered in any system design as reflections can be a source of noise in many systems.

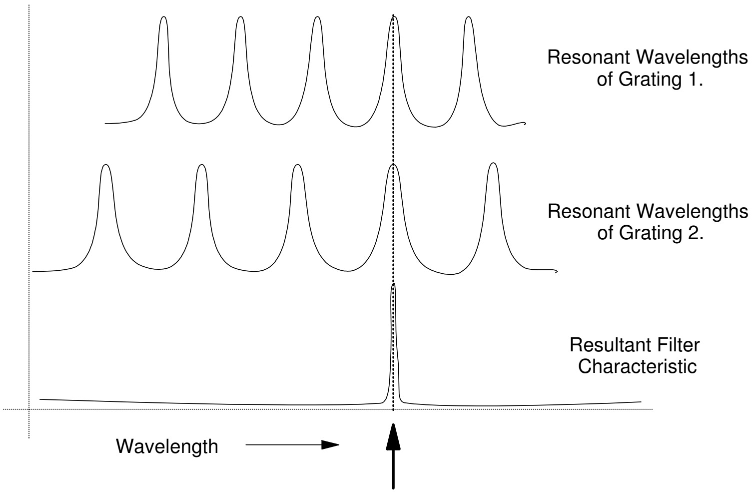

Figure 193. Cascading Fabry-Perot Filters of Different FSR

When filters are cascaded (connected in series) the resultant device operates as a new filter. The new filter has a passband where the passbands of the cascaded FP filters coincide. The passband is always narrowed. Finesse is improved very significantly as the FSR has been widened such that it is the lowest common multiple of the two FSRs of the filters that made it up. So the FSR is increased very significantly.

If two filters of the same characteristics are cascaded then we only get a narrowing of the passband. If the cascaded filters have different FSRs then the FSR of the new filter is much larger. Further discussion of the effects of cascading filters may be found in 9.4.1.1, “Cascading Filters” on page 439.

5.8.2.1 Dielectric Fabry-Perot Filters

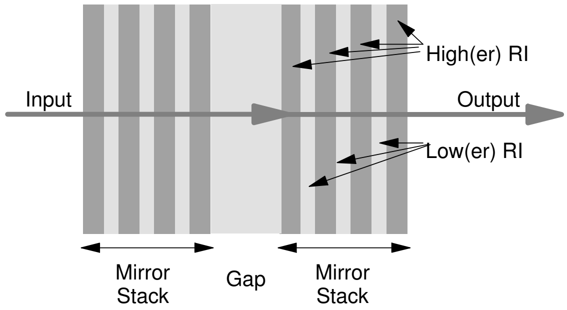

Figure 194. Fabry-Perot Filter Using Dielectric Mirrors

In microoptic technology Fabry-Perot filters are often made using a “stack” of materials of different RI as mirrors. Very thin (1/4 wavelength) layers of material with alternating (high and low) RIs are used. Typically these layers are made from SiO_2 (RI 1.46) and TiO_2 (RI 2.3) although other materials are sometimes employed. Each layer of material has a thickness of exactly 1/4 of the longest wavelength which must be handled.

By careful choice of materials and numbers of layers mirrors of any reflectivity we desire can be constructed. In addition, resonator stages (the “gaps” in the figure) may be cascaded. Thus we can control very exactly the passband and filter shape of the device.

A WDM multiplexor/demultiplexor device using dielectric FP filters is described in 5.8.5, “Dielectric Filters for WDM Multiplexing/Demultiplexing” on page 237. The principle is also used widely in semiconductor based devices. The VCSEL is constructed using an identical principle to that described here. See 3.3.14, “Vertical Cavity Surface Emitting Lasers (VCSELs)” on page 125.

5.8.2.2 Tunable Fabry-Perot Filter

The device can be tuned by attaching one of the mirrors to a piezoelectric crystal and changing the voltage across the crystal. Such a crystal can be controlled to the point that you can get accuracy of movement down to less than the diameter of an atom! The only problem is that you usually need quite a high voltage (300-500 volts) to cause the required amount of crystal deformation. Practical devices require about 1 ms to complete tuning which is quite fast for some applications but far too slow for proposed applications such as optical packet switching.

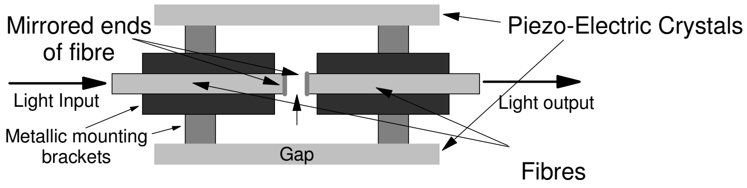

Figure 195. Tunable Fibre Fabry-Perot Filter

Figure 195 shows an ingenious variation of the Fabry-Perot filter. Two pieces of fibre are used with their ends polished and silvered. The ends are placed precisely opposite one another with a measured gap (this is the hard part). This avoids the cost of getting the light into and out of a "regular" FP filter - because it arrives and leaves on its own fibre.

The device shown is mounted on two piezo-electric crystals. By applying a voltage across the crystals we can change the distance between the ends of the fibres and hence the resonant wavelength. As mentioned above, piezo-electric crystals can be controlled such that the resulting movement is comparable with the diameter of an atom!

If you want to tune an FP filter then of course there are two alternative approaches. You can physically move the mirrors such that the size of the gap changes or perhaps you could change the RI of the material inside the cavity!

Tunable FP filters can be built by putting a liquid crystal material into the gap. The RI of the liquid crystal material can be changed very quickly by passing a current through the liquid. Reported tuning times for this type of filter are around 10 μsec but in theory sub-microsecond times should be attainable. Tuning range is 30-40 nm. Such filters are expected to be low in cost and require a very low power.

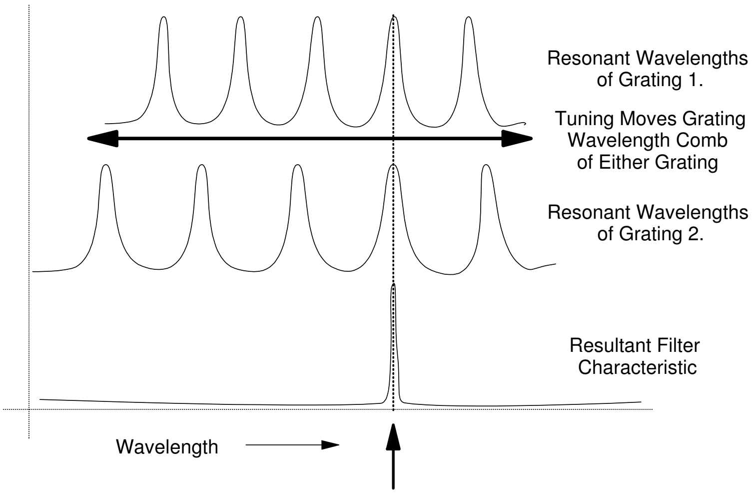

Figure 196. Cascading Tunable Fabry-Perot Filters of Different FSR

If tunable FP filters are cascaded as illustrated in Figure 196, the tuning range is extended very significantly and tuning speed is also improved. As one comb is moved it will line up with the other comb at different peaks. Thus a wide tuning range with relatively small amount of movement can be constructed.

5.8.3 In-Fibre Bragg Grating Filters