International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064

Study on Characteristics of Distributed Feedback (DFB) LASER as Light Source for Optical Fiber Communication System

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Abstract: ***This paper represents the study of light sources for optical communication through the optical fiber. For this purpose, the ideal light source characteristics have been studied. According to the study, the semiconductor LASER diodes are preferable sources over LEDs. From the family of LASER diodes, Distributed Feedback (DFB) lasers are considered as source. They have low threshold current and high efficiency as well as single wavelength characteristics. Quantum well DFB lasers are of main interest in this research letter.***

Keywords: DFB Laser, Communication Laser, Quantum Well Laser etc.

1. Introduction

The most important and widely exploited application of optical fiber is its use as the transmission medium in an optical communication link. The basic optical fiber communication system consists of a transmitter, an optical fiber, and a receiver.

The basic components of an optical communication system are shown in Fig. 1.1, below.

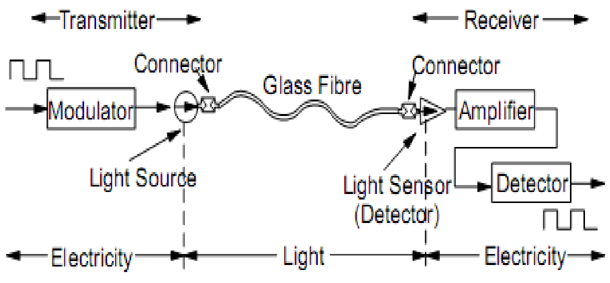

Figure 1.1: Schematic diagram of an Optical Communication System [1]

The transmitter has a light source, which is modulated by a suitable drive circuit in accordance with the signal to be transmitted. Similarly, the receiver consists of a photo detector, which generates electrical signals in accordance with the incident optical energy. The photo detector is followed by an electronic amplifier and a signal recovery unit. The source should thus meet the following most important requirements:

a) **Wavelengths:** The source wavelength should correspond to the low-loss windows of silica-namely around 1.30-µm and 1.55 µm wavelengths [2]. For a given power level at the transmitter, lower fiber losses would lead to larger repeater spacing (i.e., the propagation distance after which the signal level needs to be boosted to facilitate error-free detection at the receiver).

b) **Spectral line width**: The spectral line width of the source should be as small as possible, typically <1nm [2].This is very important because the magnitude of temporal dispersion is directly proportional to the length of the fiber and the line width of the source.

c) **Modulation speed**: To meet this requirement, one can either choose a suitable source that can be directly modulated at the desired rate or use an external modulator in tandem with a source that gives steady power output.

d) **Economical viability and acceptability:** In addition to above, it is very desired that the source be efficient, compact, reliable, durable, and inexpensive to meet the other important requirements of economical viability and acceptability.

e) Infrared radiation is produced very effectively by almost any incandes-cent filament lamp. More than 50 percent of the input wattage is radiated as infrared energy in the 770 nm to 5000 nm region. In general-purpose lighting, it is an undesirable by-product of the total radiant output. As the color temperature of a blackbody increases, the peak of its spectral output shifts away from the longer wavelength near-infrared region toward the visible region. Heat lamps which emit radiation in the mid- and far-infrared regions are available in powers up to 5000 W.

A highly versatile and reproducible source of infrared radiation is a blackbody cavity. Virtually any shape of cavity can be used, but the most popular are the cones and cylinders. Other nondischarge sources include the Nernst Glower, the Globar, and the gas mantle. The Nernst Glower and the Globar consist of slender, cylindrical rods, which are heated through metallic electrodes at the rod ends. Water cooling is required for the electrodes of the Globar, making it less convenient to use than the Nernst Glower. The gas mantle is found in high-intensity gasoline lamps. It has high visible and far-infrared output, but low near-infrared output.

Though the above sources can produce light around infrared region, these are highly expensive. The required voltages to drive them are at very high ranges. So, these sources are avoided for data transmission. Among the variety of optical sources, optical fiber communication systems almost always use semiconductor-based light sources such as light-emitting diodes (LEDs) and Laser diodes, because these sources have several advantages over the others. These advantages include compact size, high efficiency, required wavelengths of emission. Power consumption for these sources is very low. Besides, economic viability can be maintained by using semiconductor-based light sources. Above all of these advantages, these sources can be directly modulated at high speeds.

2. LASER Diodes as Light Source

2.1 Disadvantages of LEDs

LEDs have several disadvantages for which they are not used as light source for transmitting data through optical fiber. These disadvantages are:

- The maximum light output of an LED is typically very low (about 100 microwatts).
- LEDs do not produce a single light wavelength but rather a band of wavelengths.
- The light produced is neither directional nor coherent. So, LEDs are not suitable for use with single-mode fiber for this reason. It is too hard to get the light into the narrow core.
- LEDs cannot produce pulses short enough to be used at gigabit speeds.

2.2 Advantages of using semiconductor laser diodes for transmitting data through optical fiber

Almost the requirements for a light source, used for transmitting data through optical fiber, are ideally met by semiconductor laser diodes. Lasers produce far and away the best kind of light for optical communication because of;

i) **Compactness:** Most semiconductor lasers are extremely compact and of light weight; they have a chip size of 1mm3 or less. Even if a heat sink and a power supply required for driving are included, the laser system can be very compact.

ii) **Excitation by injection:** The laser can easily be driven by injection of a current in the mili amperes range with a low voltage (a few volts). Except for a power supply, no device or component for excitation is required. The direct conversion of electrical power into optical power ensures high energy conversion efficiency.

iii) **Room-temperature continuous oscillation:** Many semiconductor lasers can oscillate continuously at and near room temperature.

iv) **Wide wavelength coverage:** By appropriate choice of the materials and design of the alloy composition ratio, lasers of arbitrary wavelengths in a very wide range, from infrared to whole visible regions, can be implemented, or at least there is possibility of the implementation.

v) **Wide gain bandwidth:** The wavelength width of the gain band ofa semiconductor laser is very wide. It is possible to choose arbitrarily the oscillation wavelength within the gain bandwidth and to implement wavelength-tunable lasers. Wide-band optical amplifiers can also be implemented.

vi) **Direct and precise modulation:** By superimposing a signal on the driving current, the intensity, the frequency and the phase of the output light can readily be modulated over a very wide (from direct current to gigahertz) modulation frequency range. Lasers can be modulated (controlled) very precisely (the record is a pulse length of 0.5 femto seconds).

vii) **High coherence:** Single-lateral-mode lasers provide an output wave of high spatial coherence. In DFB and DBR lasers, very high temporal coherence can also be obtained through stable single-longitudinal-mode oscillation of a narrow (down to sub megahertz) spectrum width.

viii) **High power:** Lasers can produce relatively high power. Indeed some types of laser can produce kilowatts of power. In communication applications, semiconductor lasers of power up to about 20 mill watts are available. This is many times greater power than LEDs can generate. Other semiconductor lasers (such as those used in “pumps” for optical amplifiers) have outputs of up to 250 mill watts.

ix) **High transferability:** Because laser light is produced in parallel beams, a high percentage (50% to80%) can be transferred into the fiber.

x) **Generation of ultra short optical pulses:** It is possible to generate ultra short optical pulses of sub nanosecond to picoseconds width by means of gain switching and mode locking with a simple system construction.

xi) **Mass producibility:** The compact fundamental structure consisting of thin layers, along with fabrication by lithography and planar processing, is suitable for mass production.

xii) **High reliability:** The device is robust and stable, since the whole laser is in a form of a chip. There is no wear-and-tear factor and, for lasers of many established materials, the fatigue problem has been solved. Thus the lasers are maintenance free, have a long lifetime, and offer high reliability.

xiii) **Monolithic integration:** The features 1, 2, 9, and 10 allow integration of many lasers on a substrate. It is also possible to implement optical detectors, optical modulators and electronic devices in the same semiconductor material. Monolithic integrated devices of advanced functions can be constructed.

2.3 Important features of communication lasers

The important features of communication lasers are as follows:

i) **Spectral Width:** It is a fact that most simple semiconductor lasers do not produce a single wavelength of light. They produce instead a range of wavelengths. This range of wavelengths is called the “spectral width” of the laser. This seems to contradict the basic principle of laser operation. However, it is not so. In a semiconductor laser, a mirrored cavity is used to build up the light. By mechanical necessity, the cavity is long enough for several wavelengths to be produced.

Typically the spectral width is around 6 to 8 nm. It is interesting that these different wavelengths (modes) are not produced simultaneously - or rather their strength varies widely. What happens is that the laser will produce one dominant mode, perhaps for as short a time as a few nanoseconds, and then switch to a different mode and then to another etc. In both lasers and LEDs power delivered over the spectral width follows a bell shaped curve like that shown in Figure 2.It is difficult to determine exactly where such a curve begins and ends. So, spectral width is usually quoted as the FWHM (Full Width Half Maximum). FWHM is measured between the points on the curve where power has decayed to one half of the peak. Thus in some contexts it is also called the "3-dB point".

Spectral width is very important because:

- The wider the spectrum of the light source, the more dispersion the signal will suffer when traveling on the fiber. (This is not too bad for lasers when compared with LEDs, but is still an issue.)
- In a Wavelength Division Multiplexing (WDM) system it is desirable to pack the channels as closely together as possible in order to maximize the number of channels. The narrower the spectral width the more channels can be established.
- Frequency or phase modulation techniques or coherent detection methods can't be used unless the line width (expressed as occupied bandwidth) is significantly less than the bandwidth of the modulating signal. (100 to 1 is a good ratio.)
- Very narrow spectral width signals are subject to a number of non-linear effects which are generally thought to be undesirable.

ii) **Coherence Length and Coherence Time:** A particular laser line is emitted at a very specific wavelength corresponding to one mode (light path) in the laser's cavity. Over time this wavelength varies somewhat around a center wavelength (the amount of variation is the line width). If a sample emission, taken from one line of a laser at a particular time is of exactly the same wavelength and phase as another sample taken at a later time then the laser is said to be coherent over that time. The length of time that coherence is maintained is called the "coherence time". The length that the signal could travel in a vacuum during that time is called the coherence length. The coherence time for an LED is of the order of half picoseconds and its coherence length is around 15 microns. A simple laser may have a coherence time of perhaps half of a nanosecond and a coherence length of perhaps 15 centimeters. A very good quality narrow line width laser could have a coherence time of perhaps a microsecond and a coherence length of up to 200 meters.

iii) **Power:** The signal is attenuated as it travels on the fiber and thus the higher the signal power you use the further you can go without needing to regenerate it. In addition, theory tells us that in an optical receiver of a given type you need a certain fixed minimum amount of power per bit transmitted. If you have a working system and want to double the bit rate you must double the power (or double the receiver sensitivity). But transmitters have limits to their power49 and receivers have limits to their sensitivity. Of course, you can get a higher bit rate by reducing the attenuation (by shortening the distance between stations) thereby increasing the signal power at the receiver.

In some systems, signal power, more than fiber capacity is the limiting factor. Operating Wavelength (or Range) Of course, lasers must be able to operate on wavelengths appropriate to the system being designed. The operating wavelength of a laser depends on the materials used for lasing (in exactly the same way as the wavelength of an LED depends on the same materials) and on the geometry of the laser cavity. Frequency (Wavelength) Stability in a single-channel system using incoherent detection, a bit of instability (wander) in the laser wavelength doesn't matter too much. However, if the system is using WDM techniques, each laser must keep within its allocated band and wander matters a lot. Fabry-Perot lasers vary an enormous .4 nm per degree Celsius of temperature variation. Most of the single-mode lasers are significantly better than this, but temperature control is critical. When most lasers are modulated by OOK50 (turning them on and off) they produce a "chirp" at the beginning of each pulse (this is a transient frequency shift of as much as several gigahertz). This is a problem in WDM systems and ones using coherent receivers. Chirp is caused by two factors:

- The depletion of carriers within the active region (cavity) of the laser immediately after inversion is achieved. This causes a shift in RI of the cavity and therefore a shift in the resonant wavelength.
- By instantaneous heating effects. The cavity itself heats up - after all, the energy ("light") produced is infrared (heat) and this also changes the RI of the material in the cavity. Different types of semiconductor laser react differently to these two effects.

iv) **Switching Time and Modulation:** A fundamental operational characteristic of any laser is which modulation techniques are possible and how fast they can operate. In general, all lasers can be modulated by OOK (on/off keying) and some by FSK (frequency shift keying). Other modulation techniques require an external modulator to be placed into the light beam after it is generated.

v) **Tuning Range and Speed:** In many proposed WDM systems, transmitters, and/or receivers need to be switched between different wavelengths (channels). There are many techniques for doing this. In general, the faster the device can switch, the narrower will be the range of channels over which it can switch. Another point is that tunable lasers are seldom capable of continuous tuning over an unbroken range of wavelengths. When they are tuned they "jump" from one wavelength to another (corresponding to the resonance modes of the laser cavity).

2.3 Operating characteristics of Laser diodes

There are many operating characteristics of laser diodes; those are of primary important in its application as a source in a fiber optic communication. Some of the major performance characteristics of laser diodes are as follows:

i) **Laser threshold:** A laser is characterized by the presence of a threshold. Below the threshold current the output power is low. And as the current passing through the diode crosses the threshold value, the output power increases significantly. The emission appearing below threshold is mainly due to the spontaneous transitions, whereas above threshold it is primarily due to stimulated emission. One of the major aspects of laser diodes is a strong dependence of the threshold current and the output power on temperature. Threshold current depends critically on temperature and this dependence is approximately described by the relation

$$I_{th}(T) = I_0 e^{T/T_o} \quad (1)$$

Where I_0 is a constant and T_0 is known as the characteristics temperature of the diode. Typically, the increase in I_{th} is 0.6-1 % per °C for GaAlAs lasers and 1.2-2 % per °C for GaInAsP.

ii) **Output spectrum:** When the input current is below threshold, the laser diode behaves like an LED and the output is mainly due to spontaneous emissions and, hence, the spectrum is broad. As the current increases beyond threshold, the frequencies having a large gain and smaller cavity loss begin to oscillate and the spectrum changes significantly. The output power also increases. As the current is further increased, the output spectrum becomes sharper and the total output power also increases (figure 2.1).

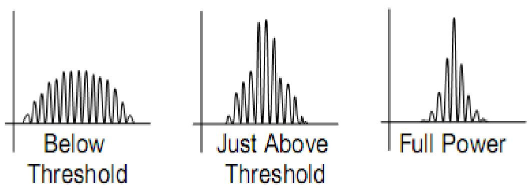

Figure 2.1: Changes in output spectrum (for index guided FP laser as example) as power is applied [1]

iii) **Radiation pattern:** In a laser structure, the optical radiation is confined in both the lateral and the transverse direction by an index step. Thus, the guiding region acts like an optical waveguide.

iv) **Modulation:** To encode information into the laser beam, the optical output of the laser must be modulated. One of the unique attractions of a semiconductor laser is the possibility of directly modulating the output of the laser by modulating the external current. Semiconductor lasers can be modulated to very high speeds of 20 GHz [2] or more.

2.4 Historical development of lasers in recent years

Several types of lasers are invented to meet the purpose for communication. Among them 1.5 µm wavelength lasers' development history and types are included in table 2.1

Table1 2.1: Low-threshold current semiconductor lasers for 1.5 µm wavelength [5]

Year	I_{th} *(mA)*	*Drive*	λ*(µm)*	*Type*	η_d*(%)*
1990	0.98	CW	1.52	BH	13
1992	0.80	Pulse	1.51	BH	9
1996	0.80		1.55	VCSEL	
2000	0.87	CW	1.61	VCSEL	
2000	0.85	CW	1.48	VCSEL	23
2000	0.70	CW	1.55	DFB	23
2000	1.00	CW	1.53	VCSEL	10
2001	0.90	CW	1.51-1.53	VCSEL	11
2001	0.80	CW	1.565	VCSEL	23
2003	0.45	CW	1.535	VCSEL	46
2003	0.70	CW	1.569	VCSEL	26
2005	0.20	CW	1.55	VCSEL	

3. Distributed Feedback LASER as the replacement of Fabry-Perot LASER

3.1 Disadvantages of Fabry-Perot Laser

Fabry-Perot (FP) lasers were used as a light source for optical fiber communication. But sometimes we have to send data over a long distance. At the time of sending data to a long distance we find that standard FP lasers have significant problems:

- 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.
- For hole burning in this laser the dominant mode is significantly reduced in power.
- Hole burning triggers mode hopping. When the strong, dominant mode decreases other modes are able to increase and become dominant (Figure 3.1). 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 the effect of the laser producing a band of wavelengths is found.

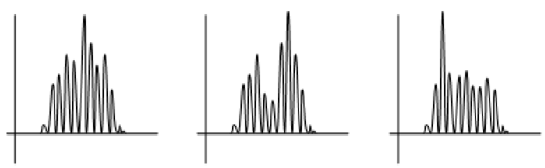

Figure 3.1: Typical mode hopping behavior in an unguided FP Laser [1]

- 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 fiber. Not only will the pulse disperse but the dispersion will be irregular and random in nature.
- In Wavelength Division Multiplexed (WDM) systems we want to carry many multiplexed optical signals on the same fiber. 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.

3.2 Distributed Feedback LASER

Distributed Feedback (DFB) lasers are one answer to the problem found with the FP laser. The idea is that a Bragg grating is put into the laser cavity of an index-guided FP laser. This is just a periodic variation in the Reflective index of the gain region along its length. The presence of the grating causes small reflections to occur at each RI change (corrugation). When the period of the corrugations is a multiple of the wavelength of the incident light, constructive interference between reflections occurs and a proportion of the light is reflected. Other wavelengths destructively interfere and therefore cannot be reflected. The effect is strongest when the period of the Bragg grating is equal to the wavelength of light used (first order grating). However, the device will work when the grating period is any (small) integer multiple of the wavelength. Thus only one mode (the one that conforms to the wavelength of the grating) can lase.

Early devices using this principle had the grating within the active region and were found to have too much attenuation. As a result the grating was moved to a waveguide layer immediately adjacent to (below) the cavity. The evanescent field accompanying the light wave in the cavity extends into the adjacent layer and interacts with the grating to produce the desired effect. In principle a DFB laser doesn't need end mirrors. The grating can be made strong enough to produce sufficient feedback (reflection) for lasing to take place. A schematic view of a DFB laser is shown in Figure 3.2.

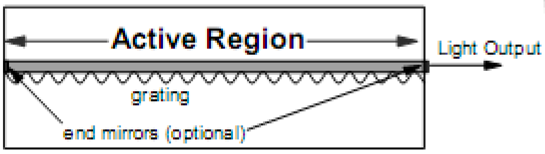

Figure 3.2: Schematic diagram of DFB Laser [1]

DFB lasers have a number of significant advantages over FP types:

- They can exhibit very narrow linewidths (of the order of 50 kHz).
- They have quite low chirp.
- They typically have a very low Relative Intensity Noise (RIN).

3.2 Implementing Quantum Wells in DFB LASER

DFB lasers are often built using a “Quantum Well” structure. When light is confined into a cavity smaller than its wavelength it behaves as a particle (quantum) rather than as a wave. In the case of semiconductor lasers if we restrict the size of the cavity, quantum behavior changes the operation of the laser in a dramatic and fundamental way.

By their nature, most semiconductor lasers are very thin (20 microns or so) in the vertical direction but this is not thin enough to cause quantum behavior. In QW lasers cavity height is reduced to around 10 or 20 nm. The width of the cavity does not need to be this restricted but of course we want it to be narrow enough to prevent unwanted “lateral” modes from forming. Cavity width is generally from 5 to 20 microns. Of course the cavity has to be many wavelengths long to get sufficient gain. In addition, it is difficult to manufacture lasers with cavities shorter than 50 microns. As with other semiconductor lasers the cavity length is typically 200 to 250 microns. This cavity geometry is called a “quantum well”. The most obvious change in laser characteristic that this brings is that the amount of material in the active region is substantially reduced. This reduces the amount of energy needed to achieve lasing and thus the lasing threshold. The result is a higher gain characteristic but a lower maximum output power than conventional (non QW) devices. In addition, quantum wells have a much reduced sensitivity to temperature change (compared to DBR and DFB structures). In the very narrow cavity available there is much less space for energy and momentum effects to occur.

Quantum Well (QW) lasers with ultra-thin active layers have been found to have superior characteristics, such as low threshold current, less temperature dependence, and narrow gain spectrum, compared to double hetero structures with bulk active materials developed in the early stage of the study of semiconductor lasers. In the QW structure, the electron and hole are confined strongly. Therefore, in order to confine even stronger for modified band structure and density of states (DOS) distribution, semiconductor lasers with low-dimensional QW structures were proposed in 1982. Quantum-Wire (Q-Wire) and Quantum-Box (Q-Box of Q-Dot) lasers are expected to have numerous advantages, such as low threshold current, high differential quantum efficiency and narrow linewidth properties due to quantum size effect. Figure 3.3 shows the schemes of each structure and schematic diagrams of DOS for each case.

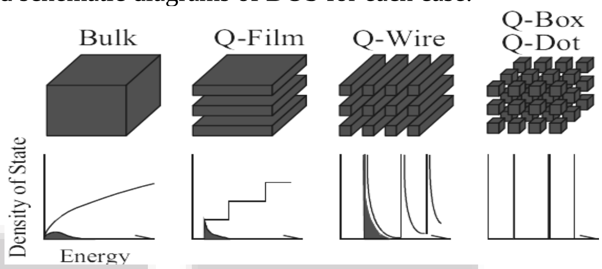

Figure 3.3: Density of states for each structure

There is another type of DFB laser which has several advantages like low threshold current and high efficiency. Periodic wire like active region is introduced in this type of laser. Figure 3.4 shows the model of that type laser.

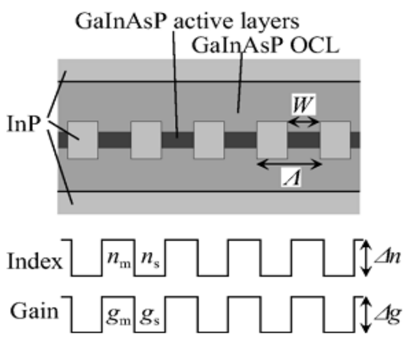

Figure 3.4: DFB Laser with wire like active region [9]

4. Results and Discussion

Two simulations have been done for quantum wire type active region DFB Laser. For simulation program Visual C++ has been used to write the code. And for output graphs (figure 4.1 & figure 4.2) Origin 7.5J software has been used. In the simulation purpose consideration the laser has two regions of different refractive indices. One has a refractive index of 3.24 of and another has a refractive index of 3.24.

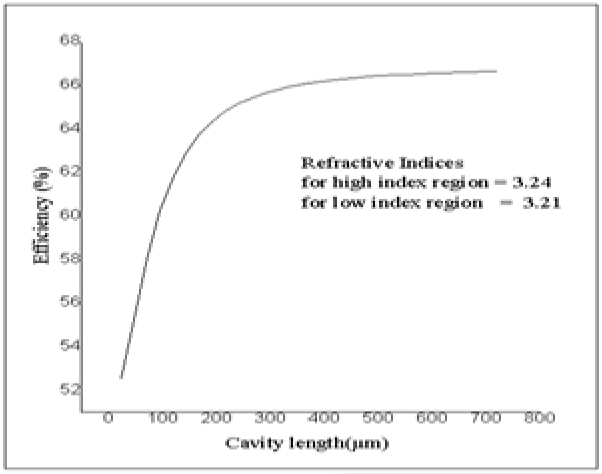

Figure 4.1: Graph for Efficiency vs. Cavity length

From the above figure it is clear that, as the cavity length is increased, the efficiency of the laser diode is increased initially. But after a certain value of the cavity length the efficiency is almost fixed. Here when the cavity length is around 200µm, the efficiency reaches around 66 %, and it becomes fixed at this value. If cavity length is lower than the wavelength of the light, no constructive interference will occur. So, cavity length must be greater than the wavelength of the light wave. The output result matches with this reasoning perfectly. The simulation expresses that at a lower value of cavity length the efficiency is lower, that means no constructive interference occurs. It is also described before that the best outcome will be found when the cavity length is equal to the light wavelength.

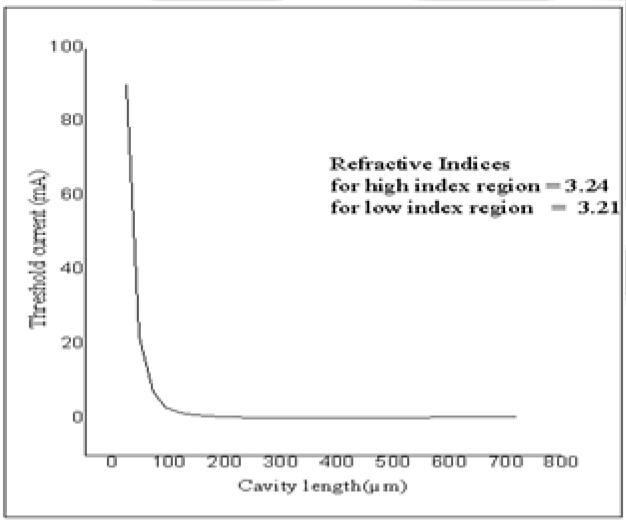

Figure 4.2: Graph for Threshold current vs. Cavity length

From the above figure it is clear that, as the cavity length is increased, the threshold current of the laser diode falls drastically. But after a certain value of the cavity length the Threshold current is almost fixed. Here when the cavity length is above 100µm, the threshold current becomes 0(mA) and it continues at this value. This is also because of the previous reasoning. That means the cavity length must be greater than or equal to the wavelength of light for interfering constructively. In the simulation this is clear that over a certain value the threshold current is lower. Lower threshold current is an important characteristic of communication lasers. Finally, it is found from the simulations that, increasing cavity length is converting the laser to a communication laser with some exclusive characteristics. The high efficiency is better for this type of laser. Again it is shown that the threshold current is almost 0 (mA), which is a nice outcome.

5. Conclusion

Comparing the two graphs (figure 4.1 and figure 4.2), found from the simulations this is clear that cavity length above 200 µm will give a highly efficient DFB laser with too much lower threshold current. In summary we can say that the DFB laser can be used as a light source for transmitting data through optical fiber.

6. Future Improvements

To vary the characteristics of the above mentioned Distributed Feedback Laser several changes can be made in their constructions, such as changing the refractive indices, phase shifting, anti reflection coating etc.

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