EFFICIENT FM-IM CONVERSION IN AN INJECTION-LOCKED FABRY - PEROT LASER DIODE

Chiranjib Ghosh
Dept. of Physics, Visva-Bharati, Santiniketan, West-Bengal, India

Taraprasad Chattopadhyay
Dept. of Physics, Visva-Bharati, Santiniketan, West-Bengal, India

ABSTRACT

In this paper, we have studied the frequency modulation to intensity modulation (FM-IM) conversion property of a Fabry-Perot laser diode (FPLD) injection locked to a spectrally pure single mode master FPLD lasing at 1550.3 nm. The master FPLD is directly modulated at 5 KHz and 3 MHz which produces an IM-FM lightwave at the output of the injected slave FPLD. The injection-locked slave FPLD possesses good amplitude limiting property which reduces the output IM by several tens of dB. The FM of the input injection master lightwave undergoes conversion to IM in the injection-locked slave FPLD which produces a post-detection output voltage at the output of the photodiode. Typical IM index~10% resulting from FM-IM conversion has been measured in the experiment. The theory of FM-IM conversion agrees well with the experiment when the master laser IM index is small.

Key words: Frequency Modulation, Intensity Modulation, Injection Locking, Modulation Conversion, Fabry-Perot Semiconductor Laser.


http://www.iaeme.com/IJECET/issues.asp?JType=IJECET&VType=7&IType=2

1. INTRODUCTION

Optical injection locking of semiconductor laser is a nonlinear phenomenon [1-5]. Injection-locked laser diode as a nonlinear device shows some nonlinear phenomena such as optical frequency modulation (FM) to optical intensity modulation (IM) conversion. This FM-IM conversion ushers the demodulation of optical FM signal by using a single photodiode. This method of FM demodulation does not require an FM
discriminator. The concept of FM-IM conversion in injection-locked semiconductor laser was reported by several workers [6-7]. Later on, optical FM-IM conversion was reported in various media such as in interferometer [8], optical fiber [9, 10], fiber grating [11] etc. Response of slave laser diode injected by a master laser carrying amplitude and frequency modulation has been studied by Lau and Wu [7] in 2004. But, they have not thrown much light into the mechanism of direct frequency modulation of the master laser in the low modulation frequency domain, particularly below 10 MHz. It has been established that when the modulation frequency is high (typically > 50 MHz) the frequency modulation is related with the line width enhancement factor (LEF) as provided by Koch-Bowers’ formula [12]. But, in the low frequency region, the thermal effect on FM generation dominates over the normal chirping linked with amplitude-phase coupling of the master laser. This fact of direct FM generation [13-15] should be focused in detail in calculating the optical FM-IM conversion taking place in an injection-locked slave laser.

In this paper, we have developed a complete theory which takes the thermal effect as well as the amplitude-phase coupling effect into consideration in the process of direct FM generation in the master laser. We have calculated the optical FM-IM conversion when the modulation frequency is low, typically less than 10 MHz. The converted IM has been detected in a photodiode and the output IM index estimated. The theory and experiment on FM-IM conversion show a good fit except for a slight departure at higher values of input IM index.

2. ANALYSIS

The schematic circuit diagram of the FM-IM conversion experiment is shown in Figure. 1.

![Figure 1. Schematic circuit diagram for FM-IM conversion measurement](image-url)
In this section, we calculate the output intensity modulation index of the slave laser diode injection locked to an FM-IM master light wave. Four kinds of modulation conversion are involved in the injection locking process. These are:

(i) IM to IM conversion
(ii) IM to FM conversion
(iii) FM to FM conversion, and
(iv) FM to IM conversion.

Among these, IM to FM and FM to FM conversion processes are not of interest in this paper since the photodiode does not respond to optical FM signals. The photodiode only responds to its input intensity modulation and produces an output current proportional to the intensity modulation. The process IM to IM conversion injection locked diode produces negligible effect at the detector output due to amplitude limiting property of the locked laser diode. The output IM of the locked slave laser is several orders of magnitude down \([16, 17]\) relative to input IM. As a result, the only modulation conversion process remaining which produces considerable output of the photodiode is the FM to IM conversion.

In direct modulation of the laser diode, the bias current of the LD is modulated where the modulation signal is applied to the LD through a bias tee. Direct modulation of the LD produces both intensity modulation and frequency modulation of the LD output.

The intensity modulation of the master LD is described as

\[
I(t) = I_0 \left(1 + m_i \sin \omega_m t\right)
\]

Corresponding power modulation is expressed as

\[
P_{in}(t) = P_{in0}\left(1 + m_i \sin \omega_m t\right)
\]

where \(I_0\) is the average intensity, \(P_{in0}\) is the average optical power, \(m_i\) is the intensity modulation index and \(\omega_m\) is the radian frequency of intensity modulation.

The frequency shift of the master LD due to direct modulation is given by Koch-Bowers formula \([12]\) as

\[
\Delta \nu(t) = -\frac{\alpha}{4\pi} \frac{\partial}{\partial t} \ln P_{in}(t)
\]

where \(\alpha\) is the line width enhancement factor of the FPLD. The phase change of the output light wave of the master LD is calculated as

\[
\phi(t) = 2\pi \int \Delta \nu(t) dt
\]

where \(\phi_0 = \frac{\alpha}{2} \ln P_{in0}\) and \(m_f = \frac{\alpha}{2} m_i\) is the FM index. Here, we have assumed \(\ln(1 + m_i \sin \omega_m t) \approx -m_i \sin \omega_m t\) since \(m_i \ll 1\).

The light wave injected into the slave laser can be written as

\[
E_{inj}(t) = \sqrt{P_{in0}} \left(1 + m_i \sin \omega_m t\right) e^{j(\omega_m t - \phi_0 - m_f \sin \omega_m t)}
\]

where \(P_{in} = P_{in0}\left(1 + m_i \sin \omega_m t\right)\)
In (5), the actual electric field is the real part of the complex representation which is normalized so that $|E_{inj}|^2 = P_{inj}$. $m_I$ is the IM index.

which is related with the amplitude modulation index $m_a = \frac{m_I}{2}$ assuming $m_I << 1$. $\omega_e$ is the radian frequency of the injected lightwave.

The FPLDs are thermoelectric current (TEC) controller. The TEC controller controls the temperature of the active region within 0.002°C observed over a long term of 24 hours. So, far as the short term effect is concerned, the active region temperature varies in direct proportion to bias current modulation amplitude ($I_{mod}$). As per available literature, the wavelength of InGaAs FPLD operating at 1550.3 nm increase at the rate of $\frac{\Delta \lambda}{\Delta T} = 0.4 nm/0°C$ which corresponding to a fall in LD operating frequency of $\frac{\Delta \nu}{\Delta T} = -\frac{c}{\lambda^2} \Delta \lambda/0°C$. where $c=3\times10^8 m/sec$ is the vacuum velocity of light. The thermal frequency shift of the FPLD is calculated as

$$\Delta \nu_{th} = -123.73 \times 0.4 \times 0.002 \times I_{mod} = -99 I_{mod} MHz.$$

At low temperature below 50 MHz, thermal frequency modulation of the master LD is the dominant effect giving rise to FM-IM conversion in the slave FPLD.

Output light wave of the injection-locked FPLD is given by in complex representation

$$E_{out}(t) = E_o(t) e^{i(\omega t + \theta_o(t))}$$

(7)

where $E_o(t) = E_o(1 + m_o \sin(\omega_m t + \xi))$

(8)

Actual field is the real part of (7). $m_o$ is the amplitude modulation index output so that $2m_o$ is the output intensity modulation of the slave LD. The amplitude governing equation [4] of the injected slave LD can be written as

$$\frac{2Q}{\omega_0} \frac{dE_{inj}(t)}{dt} = -2 \left[ C_1 E_{inj}(t) E_o(t) \right] \left[ \frac{|E_{inj}(t)|^2}{E_o^2} \right] \left[ \cos(-\phi_0 + m_o \sin \omega_m t - \theta_o(t)) + 1 \right] + \frac{2Q}{\omega_0} \left[ \frac{|E_{inj}(t)|^2}{E_o^2} \left( -\phi_0 + m_o \sin \omega_m t - \theta_o(t) \right) \right] \frac{d\theta_o(t)}{dt}$$

(9)

where $C_1 = \left( n - \frac{1}{n} \right) l \alpha_m$, $C_2 = C_1 - 2$. Here $l$ is the length of the cavity, $\alpha_m$ is the mirror loss and $n$ is the refractive index of the active region. The active region is made of InGaAs for lasing at 1550 nm wavelength range. The injection power is much less than the free running output power of the slave LD so that the injection locking takes place in under driven condition. In the steady state of locking, $\frac{dE_{inj}}{dt} = 0$ and $E_{o} = E_f$ where $E_f$ is the free running output amplitude which is normalized so that $|E_f|^2 = P_f$ and $|E_{inj}|^2 = P_o$. Here, $P_f$ is the free running output power and $P_o$ is the output power of the locked slave LD.
The output angle modulation is assumed to be of the form

$$\theta_0(t) = \theta_{av} + \theta_m \sin \omega_m t$$

(10)

where $\theta_{av}$ is the average phase of the output angle modulation.

For modulation frequency $f_m \leq 1GHz, \theta_m \approx m_f$ [3,6].

Taking $\omega_m = \omega_0, \theta_{av} = \tan^{-1} \alpha$

(11)

where $\omega_0$ is the free-running radian frequency of the LD.

Substituting (8) in (9) and equating the dc terms and coefficients of $\sin \omega_m t$ and $\cos \omega_m t$ from both sides of (9) we get the following equations as

$$\cos(\phi_0 + \theta_{av}) = 0$$

(12)

since $C_1 - C_2 - 2 = 0$.

$$m_0 \begin{bmatrix} -x_1 & x_2 \\ x_2 & x_1 \end{bmatrix} \begin{bmatrix} \sin \xi \\ \cos \xi \end{bmatrix} = \begin{bmatrix} 0 \end{bmatrix}$$

(14)

where

$$x_1 = \frac{2Q \omega_m}{\omega_0}$$

(15)

$$x_2 = \frac{2C_2 E_o^2}{|E_f|^2}$$

(16)

$$x_3 = -\frac{2Q |E_{inj}|}{\omega_0 E_o} (m_f \omega_m + \Delta \omega_{TH})$$

(17)

$m_f = a m_a$ and $\Delta \omega_{TH}$ is the thermal frequency shift of the master FPLD for a given bias current modulation amplitude $(I_{mod})$. Squaring and adding the equation pair in (14), we get

$$m_0^2 = \frac{x_3^2}{x_1^2 + x_2^2}$$

(18)

$$\therefore \quad m_0 = \frac{|x_3|}{(x_1^2 + x_2^2)^{1/2}}$$

(19)

The output IM index of the slave laser is $m_{0l} = 2m_0$ and the input IM index is $m_l = 2m_a$ assuming the IM index to be small compared with unity. Then, (19) can be recast as

$$m_{0l} = \frac{2|x_3|}{(x_1^2 + x_2^2)^{1/2}}$$

(20)
Taking $n=3.7$ for InGaAs LD at 1550.3 nm, cavity length $l=0.6\text{mm}$ and mirror loss $\alpha_m=10\text{cm}^{-1}$, we get $C_1=2.0578$ and $C_2=0.0578$. In experiment, $P_{inj}=1\text{mW}$ and $P_f=4.83\text{mW}$. Assuming low-level injection (i.e; $P_{inj}<P_f$), $E_o=E_f$. The value of line width enhancement factor ($\alpha$) is taken as 3.3 to LD bias current of 80 mA [18]. We have calculated $m_{o1}$ as a function of $m_f$ from (20). It is plotted in fig. 2. The plot is linear and the experimental data show a good fit with the theoretical plot at modulation frequencies of 5 KHz and 3 MHz.

![Figure 2](image)

**Figure 2.** Variation of output slave laser intensity modulation index resulting from FM-IM conversion with the input master laser intensity modulation index.

### 3. CONCLUSION

In this paper, we have developed a self-sufficient theory of optical FM-IM conversion in an injection-locked slave laser when the master laser is directly modulated. The low modulation frequency region, particularly below 10 MHz is related with thermal modulation of master laser frequency which is the dominant effect in this frequency range. This low frequency response of the slave laser as an FM-IM converter has been investigated experimentally and compared with the theoretical result. The theory shows a good fit with experimental data except at high values of master laser IM index when slight departure is noticed. The departure originates from the fact that we
Efficient FM-IM Conversion in an Injection-Locked Fabry - Perot Laser Diode

have assumed small values of the master laser IM index in theory. An efficient FM-IM conversion has been noticed leading to converted IM index level -10% at the output of the slave laser. The injection-locked slave laser together with a photodiode can act as an FM-IM converter-detector demodulator.

REFERENCES


