Chapter - 5

Measurement of second harmonic distortion of the detected signal in an IM-DD fiber optic link when the input IM is second harmonic contaminated

5.1. Introduction:
With the rapid development of optical communication system in the 21st century, the research on high speed optical modulation and detection is being carried out all over the globe. The most simple, widely used and commercially viable fiber-optic communication is the IM-DD communication. The modulation format used here is the intensity modulation (IM) and the detection scheme employed is the direct detection (DD) in a photodiode. In any communication system, message signal distortion at the output is an important factor for assessing the reliability of the communication link.

Survey of relevant literature indicates that the message signal distortion related studies have been done by many authors [5.1-5.20]. Generation of non-linear distortion in directly modulated external cavity lasers has been investigated by Premaratne et al. [5.6]. Investigation on harmonic distortion, intermodulation distortion, signal clipping and effect of relative intensity noise (RIN) on subcarrier multiplexed IM-DD optical link has been carried out by some authors [5.1-5.3]. Harmonic distortion and the intermodulation distortion in direct modulation arises from the nonlinearity of the light power vs. laser diode (LD) bias current characteristics (L-I curve). Wang et al. [5.7] have measured intermodulation and harmonic distortion in DFB lasers with modulation at microwave frequencies. Majewski et al. [5.8] have developed a circuit theoretic model for the estimation of harmonic distortion in DFB lasers diodes. Haeng et al. [5.9, 5.10] have carried out experiments on suppression of second harmonic distortion in directly modulated DFB lasers with the help of optical injection locking. Kwang, Ming and Kenton [5.11] have reported significant reduction of second and third harmonic distortions in a semiconductor laser directly modulated at 5 GHz with a reduction level of 15dB and 23dB respectively. A review of broadband access network using optical-fibers including point-to-point and point-to-multipoint communication has been described by Koonen et al. [5.12]. Applications of subcarrier multiplexing including various kinds of analog and digital transmission systems have been reported by Darcie et al. [5.13]. Arsat et al. [5.14] have reported a subcarrier multiplexed [SCM] technique for the
transmission of data in a radio over fiber system. The transmission performance of a microcellular networks based on radio over fiber system has been investigated by Chandra and Chaturvedi [5.15]. Generation of harmonic distortion in GaAlAs lasers due to the non-linearities of the device has been described in [5.16]. Theory of second harmonic distortion in AM response of FP and DFB lasers have been developed by Morthier et al. [5.17]. Effect of lateral loss of a vertical cavity surface emitting laser (VCSEL) on the second harmonic distortion has been studied theoretically by Chui and Yu [5.18]. No investigation seems to be carried out when the input IM signal is itself second harmonic contaminated in its modulation.

In this chapter, the author has investigated and measured the output second harmonic modulation level when the input modulating signal is second harmonic-contaminated.

5.2. Description of experimental set up:

The experimental set up using a laser diode, a photodiode and other accessories supplied by THOR LABS, USA is shown in figure 5.1. The Fabry-Perot laser diode (FPLD) lasing at the central wavelength of 1557.1 nm operates at 23°C which is maintained by a Thermoelectric current (TEC) controller (Model: ITC4001). The dc bias current \( I_{dc} \) and the RF modulation current \( I_{mod} \) is applied to the laser diode (LD) through a bias tee. The bias tee is incorporated in the mount of the LD. The LD output is simultaneously intensity modulated (IM) and frequency modulated (FM). The intensity modulated lightwave is fed to an InGaAs photodiode (PD) having a bandwidth of 1.2 GHz which responds to the IM part only and does not respond to the FM part. The PD output current is proportional to the input optical power to the PD. The output of the PD is connected to a load resistance \( R_L \). The IM lightwave is detected by the PD and it power spectrum is displayed in an Agilent microwave spectrum analyzer (Model: E4403B, 9 kHz - 3 GHz). The input and the output second harmonic distortion can be measured using this spectrum analyzer. The fundamental modulation frequency used in experiment is 100 MHz and the second harmonic frequency is at 200 MHz. The load resistance of the PD is 50 \( \Omega \). The threshold current of the LD is 41.6 mA. The RF modulation source available in our laboratory is in the range 100 MHz-400 MHz. 1557.1 nm wavelength of the LD falls in the C-band (1525 nm-1565 nm) of the infrared (IR) spectrum. Fiber loss is minimum at this wavelength which stands at 0.2 dB/Km. Also, optical amplifiers like EDFA are available at this wavelength and DWDM
communication can be implemented over this band. Since 1557.1 nm wavelength falls in the telecommunication band, message signal distortion is of serious concern. As such, second harmonic distortion being a major source of harmonic distortion in IM-DD fiber-optic link has motivated us to study its effect on the link. The author has used Fabry-Perot laser diode since they are cheap.

1557.1 nm wavelength has also application in infrared radio-astronomy. At this wavelength, the atmospheric opacity is small, sky transparency is high and sky brightness is low so that ground based astronomical observations can be made.

The author has used an optical power meter having model no. - PM100D, the photodiode with model no. – DEC01CFC and a pigtailed LD mount with model no. LM9LP, all supplied by THOR LABS, USA.

In this chapter, the author has measured the detected RF signal distortion in an IM-DD fiber optic link when the input message signal contains a small amount of second harmonic distortion. The dependence of output second harmonic modulation distortion on the input message signal distortion has been found to be linear in the logarithmic scale.

5.3. Analysis:

Let the RF modulating signal voltage be represented as

\[ V_{\text{mod}} = V_{m1} \sin \omega_m t + V_{m2} \sin 2\omega_m t \]  

(5.1)

where \( V_{m1} \) and \( V_{m2} \) are the voltage amplitudes of the fundamental and second harmonic respectively, and \( \omega_m \) is the radian frequency of the fundamental RF signal. The powers of the RF signal and the second harmonic are

\[ P_{\text{mod} f} = \frac{V_{m1}^2}{2R} \]  

(5.2)

and

\[ P_{\text{mod} 2} = \frac{V_{m2}^2}{2R} \]  

(5.3)

respectively. The subscript ‘f’ stands for fundamental and subscript ‘2’ stands for second harmonic.

Here \( R \) is the input impedance of the LD at its direct modulation port. For the LD under consideration, the different physical parameters are shown in table 5.1.
Figure 5.1: Experimental setup for measuring second harmonic distortion in an IM-DD Fiber-Optic link. MSA: Microwave spectrum analyzer.
Table 5.1
Values of different physical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lasing wavelength ($\lambda_c$)</td>
<td>1557.1 nm</td>
</tr>
<tr>
<td>LD temperature</td>
<td>23 °C</td>
</tr>
<tr>
<td>Threshold current of LD</td>
<td>41.6 mA</td>
</tr>
<tr>
<td>DC bias current of LD</td>
<td>50 mA-100 mA</td>
</tr>
<tr>
<td>InGaAs PD bandwidth</td>
<td>1.2 GHz</td>
</tr>
<tr>
<td>LD modulation port input resistance</td>
<td>50 Ω</td>
</tr>
<tr>
<td>Load resistance of PD</td>
<td>50 Ω</td>
</tr>
<tr>
<td>Responsivity of photodiode</td>
<td>0.88 mA/mW</td>
</tr>
</tbody>
</table>

The modulation power ($P_{\text{mod}}$), measured by the Microwave spectrum analyzer (MSA), contains fundamental at 100 MHz and a second harmonic at 200 MHz frequency. The intensity (or power) modulation of LD is expressed as

$$P(t) = P_0 (1 + m_1 \sin \omega_m t + k m_2 \sin 2\omega_m t)$$  \hspace{1cm} (5.4)

where $m_1$ and $m_2$ are the fundamental and second harmonic intensity (or power) modulation indices and $k$ is a slope parameter of the LD modulator for the second harmonic. The detected signal voltage is calculated as

$$V_{D0} = \eta P(t) R_L$$

$$= \eta R_L P_0 (1 + m_1 \sin \omega_m t + k m_2 \sin 2\omega_m t)$$  \hspace{1cm} (5.5)

where $\eta$ is the responsivity of the PD in mA/mW, $R_L$ is the load resistance of the PD. The factory supplied data on the LD modulation response shows that there exists a very small downward slope in the modulation response over the modulation frequency band 100 MHz-200 MHz. This is taken into account by the slope parameter $k$. The detected fundamental and second harmonic voltages of the output of the PD are given as

$$V_{D1} = \eta R_L P_0 m_1$$  \hspace{1cm} (5.6)
and

\[ V_{d2} = \eta R_L P_0 k m_2 \]  \hspace{1cm} (5.7)

respectively.

To calculate \( \eta \), we have measured the detected output voltage in response to input optical power which is plotted in figure 5.2. The slope of this linear plot is proportional to \( \eta \). When the magnitude of this slope is divided by \( R_L \), we get the value of \( \eta \) in mA/mW.

Now the second harmonic distortion \( (D_{in}) \) of the input RF signal and the same \( (D_{out}) \) for the detected RF signal output are given in dB by

\[ D_{in} = 20 \log_{10} \left( \frac{V_{m2}}{V_{m1}} \right) \]  \hspace{1cm} (5.8)

\[ D_{out} = 20 \log_{10} \left( \frac{km_2}{m_1} \right) \]  \hspace{1cm} (5.9)

respectively. Now, we can write

\[ \frac{V_{m2}}{V_{m1}} = \left( \frac{P_{m2}}{P_{m1}} \right)^{1/2} \]  \hspace{1cm} (5.10)

Then, from (5.8) and (5.10) we write

\[ D_{in} = 10 \log_{10} \left( \frac{P_{m2}}{P_{m1}} \right) dB \]  \hspace{1cm} (5.11)

\[ = 10(\log_{10} P_{m2} - \log_{10} P_{m1}) dB \]

\[ = (P_{m2} |_{dBm} - P_{m1} |_{dBm}) dB \]  \hspace{1cm} (5.12)

\( P_{m2} \) and \( P_{m1} \) are given in dBm taking the reference power as 1 mW.

Thus,

\[ P_{m1} |_{dBm} = 10 \log_{10} \left( \frac{P_{m1}}{1 mW} \right) \]  \hspace{1cm} (5.13)

and

\[ D_{out} = 20 \log_{10} \left( \frac{V_{d2}}{V_{d1}} \right) = 20 \log_{10} \left( \frac{P_{d2}}{P_{d1}} \right)^{1/2} \]

\[ = 10(\log_{10} P_{d2} - \log_{10} P_{d1}) dB \]

\[ = (P_{d2} |_{dBm} - P_{d1} |_{dBm}) dB \]  \hspace{1cm} (5.14)

Measured values of output second harmonic distortion, \( D_{out} \), is plotted as a function of measured values of input second harmonic distortion, \( D_{in} \), in figure 5.3. The plot in units of dB is linear. The plot has a positive slope. The output second harmonic distortion is smaller than the input second harmonic distortion because of the negative slope factor \( k \) in the modulation response over the frequency band of 100 MHz- 200 MHz.
Figure 5.2: InGaAs photodiode response. Load resistance of the PD = 50Ω.
The value of $k$ has been determined experimentally from the plot. The average value of $k$ comes out as $k = -0.3$ dB.

The fundamental modulation index is calculated as

$$m_i = \frac{I_{\text{mod}}}{(I_{\text{bias}} - I_{\text{th}})} \quad (5.15)$$

where $I_{\text{mod}} = V_{\text{mod}} / R_L$. Here, $I_{\text{mod}}$ = fundamental modulation current, $V_{\text{mod}}$ = fundamental modulation voltage, $I_{\text{bias}}$ = LD bias current, $I_{\text{th}}$ = LD threshold current.

Apparently, it seems that the second harmonic problem can be removed through filtering and external modulation. But, external modulator nonlinearity gives rise to harmonic distortion of the modulated signal unless the driving signal amplitude is kept at very low level which leads to low modulation index. For a nearly monochromatic RF source, the second harmonic component can be eliminated through selective filtering. However, for a multi-frequency source, many such filters are required leading to complexity in design.

Higher order harmonic distortions are smaller than the second harmonic distortion. Second harmonic distortion, as observed in our experiment, is the major source of distortion. However, third and higher order distortions need further investigation.

**5.4. Conclusion:**

The input RF source is inherently contaminated by second harmonic. When the fundamental modulation frequency is chosen as 100 MHz, the second harmonic at 200 MHz is automatically generated in the synthesized source in a small amount which cause second harmonic distortion.

In this chapter, the author has measured the second harmonic distortion of the detected signal in an IM-DD fiber optic link when the input modulation contains a small amount of second harmonic distortion. The variation of output second harmonic distortion with the input second harmonic distortion shows a linear nature. The measured second harmonic distortion is slightly smaller than the input second harmonic distortion. This is due to the existence of small negative slope factor in the modulation response of the laser diode over the modulation frequency band of 100 MHz to 200 MHz.

From our experiment it is inferred that the input second harmonic distortion level does not change much during its transmission over the IM-DD link. However, in long haul optical communication, the effect of optical fiber on signal propagation needs further investigation.
Figure 5.3: Output second harmonic distortion as a function of input second harmonic distortion in the IM-DD fiber-optic link.
For a single tone modulation an optical notch filter and for wideband multitone modulation an optical band stop filter can be used before detection to eliminate second harmonic distortion.

References:


