RMS Spectral Width of VCSELs and their effects on link performance

Application Note 5010

Abstract

Spectral width is an important parameter in determining the performance of a Gigabit Ethernet Optical Link. The paper attempts to explain to what extent spectral width and the shape of the optical spectrum impact the link performance.

Introduction

Lasers (Light Amplification by Stimulated Emission of Radiation) are monochromatic sources, but in practice they usually emit light that spans a narrow wavelength range. Fabry Perots, VCSELs and DFBs are some examples of the type of lasers used in the industry.

Qualitatively, the Spectral width is a measure of how effectively optical power output by the laser is confined to the center wavelength of emission. Spectral width is always nonzero even if there is only a single mode operating, due to the random nature of spontaneous emissions. If power is spread across modes away from the center wavelength, the broader the spectral width is, and vice versa.

Vertical Cavity Surface Emitting Lasers (VCSELs) are single longitudinal-mode, multiple transverse-mode devices. Typically, the optical spectrum of a VCSEL is narrower than that of a Fabry Perot (FP) laser and broader than that of a Distributed Feedback Laser (DFB) which is designed for single wavelength operation.

IEEE document 802.3 (2000), section 1.4.238 states that “rms spectral width is the optical wavelength range as measured by ANSI/EIA/TIA 455-127-1991 (FOTP-127).”[1]

Accordingly, the spectral width is given by,

$$\text{Spectral - width(rms)} = \sqrt{\sum_{i=1}^{n} \frac{p_i}{P_o}.(\lambda_i - \lambda_o)^2}.1$$

where λ_o is the mean wavelength, λ_i and p_i are the wavelength and power respectively at a particular point on the spectrum and P_o is the total power output. The number of points taken into account is determined by the resolution of the measurement device used.

It is important to differentiate between the rms spectral width and FWHM (full width at half maximum) which is defined as the wavelength difference between the center and the point at which the power is 50% of the maximum.

An optical spectrum analyzer like the Agilent 86140B is the most popular and preferred tool for these measurements. It can be used to measure the rms spectral width and the FWHM of a laser source directly. [2] The following picture is taken from an Agilent 86149B on a Fabry Perot Laser.

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Impact of spectral width on link length

The 1000 BASE-SX Gigabit Ethernet specification for maximum spectral width (rms) is 0.85 nm. [3]

The following curve illustrates the effect of laser spectral width on the link length. The graph was generated using the Gigabit Ethernet link budget. Transmitter and receiver characteristics used in the graph were similar to that of the Agilent HFBR-5911L/AL.

We can see that the link length changes by about 20 m when the spectral width changes from 0.1 nm to 0.85 nm.

However, as the spectral width goes beyond the spec limit, i.e., beyond 0.85 nm, we can see that the curve gets steeper. This is borne out by Figure 3 which shows that the rate of decrease of link length increases as the spectral width increases.

Therefore, the spectral width performance on the link length is not very substantial as long as it is below 0.85 nm. However, if it is much higher than the specified limit, it could impact the link length substantially.

At the same time, modal noise is sometimes found to be higher when a multimode fiber is used with a highly coherent source. Coherence length is the distance by which a portion of the beam can be delayed relative to the rest of the beam and still interfere with itself. Rays of light travel along the fiber at different speeds. When the path difference between rays exceeds the coherence length, the contrast between bright and dark spots also decreases, thus reducing the modal noise. Hence, modal noise can be lower if the spectral width is higher.

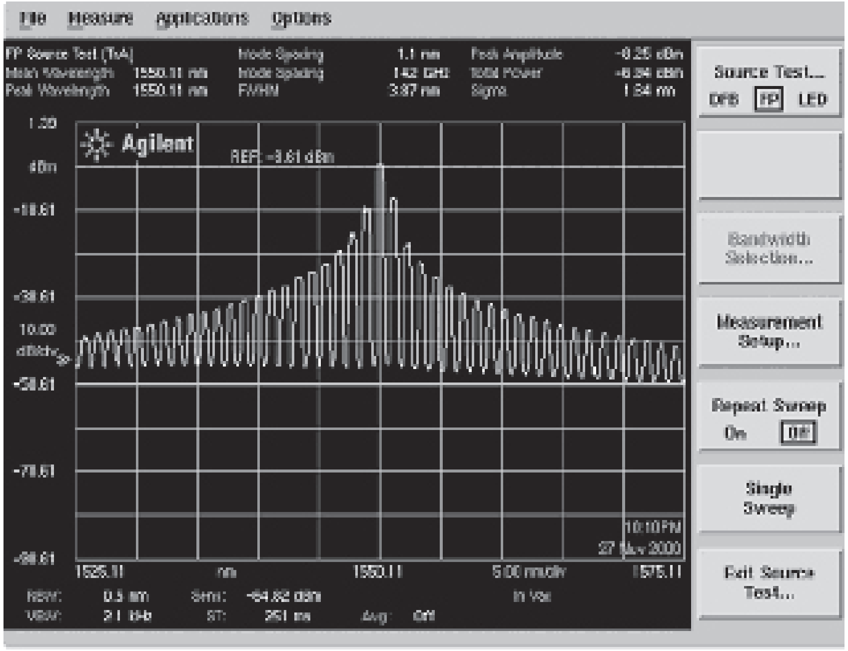

Figure 1. Sample Output from an Agilent 86140B on a Fabry Perot Laser

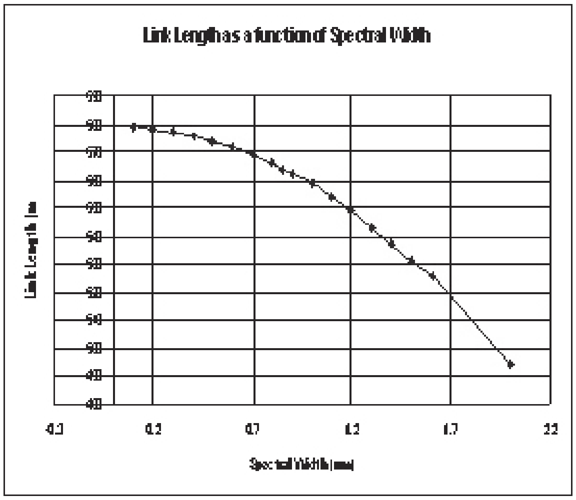

Figure 2. Link length as a function of Spectral Width

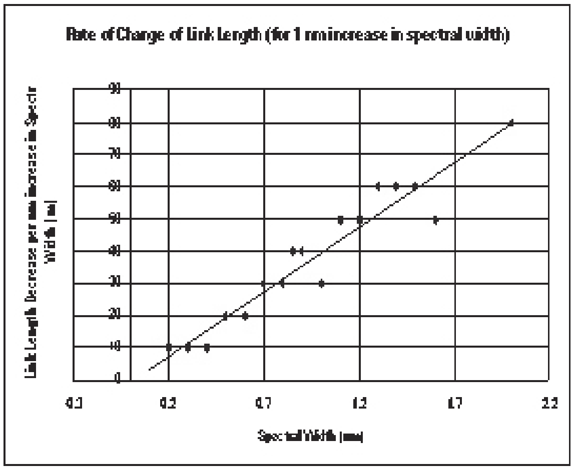

Figure 3. Link length deteriorates quicker at higher spectral width

Effect of Optical Spectrum Shape on the Mode Partition Noise

The rms spectral width is however, a lumped parameter. While it gives useful information on the optical spectral characteristics, it does not give us too much information about the actual shape of the spectrum.

At this point, it is important to distinguish between the time-average shape of the spectrum and the instantaneous shape of the spectrum. The time average shape of the spectrum is the optical spectrum sans the mode partition noise. On the other hand, the instantaneous shape of the optical spectrum can vary as a function of time, revealing the presence of mode partition noise.

Mode partition noise (abbreviated as MPN) is characterized by the time-varying partition of power contained in the various modes. Mode partition noise contributes to the total power penalty and can reduce the link performance and maximum link length.

While the change in the instantaneous spectrum shows the presence of MPN, it is hard to predict what the *time-average* shape of the curve does to the MPN contribution in a VCSEL. To illustrate this, we can take a look at two possibilities - in one case, the time-averaged optical spectrum shape is purely Gaussian, centered at the mean wavelength with an rms spectral width of s. In the other case, the rms spectral width is maintained the same (s), but the spectrum simply consists of three lines, separated by a wavelength spacing of Dl. Thus, s and Dl are related by

$$\sigma = (\Delta\lambda).\sqrt{\frac{2}{3}}$$

Mode partition noise power penalty in a link, denoted by a_{mpn} is a function of the mode partition noise variance $\sigma_{mpn}{}^2$.

$$a_{mpn} = 5.\log\left(\frac{1}{1 - Q^2.\sigma_{mpn}{}^2}\right) \ldots (2)$$

Q is dependent on the bit error rate aimed for. In the case of 10^{-12} BER, the value of Q is equal to 7.

When the optical spectrum is purely Gaussian, the mode partition noise variance can be calculated by means of a formula, given by [4]:

$$\sigma_{mpn} = \frac{k}{\sqrt{2}}.\left(1 - \exp(-\beta^2)\right) \ldots (3)$$

where b is a dimensionless quantity.

$$\beta = \pi \mathrm{BLD}\sigma \ldots (4)$$

B is the bit error rate, L is the link length and D is the dispersion parameter of the fiber used.

However, the mode partition noise for the three mode spectrum that we've chosen cannot be calculated by the above formula. The mode partition noise in that case, is given by:

$$\sigma_{mpn} = k.\sqrt{\left[\sum_{i=1}^{3} f_i^2.\mathrm{A}_i - \left(\sum_{i=1}^{3} f_i\ .\mathrm{A}_i\right)^2\right]}$$

... (5)

Where A_i are the normalized powers at the three modes. Note that in our case the power is split equally, giving $A_1=A_2=A_3=1/3$. f_i is the signal waveform at the receiver after the decision circuit has sampled the incoming signal. f_i reduces to the following:

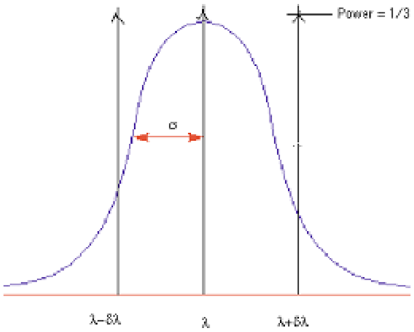

Figure 4. Three mode and Gaussian spectrum

$$f_i = cos(\pi \mathrm{BLD}.(\lambda_i - \lambda_0)) \ldots (6)$$

λo is the mean wavelength (the central mode among the 3 modes).

Using equations (5) and (6), we get,

$$\sigma_{mpn} = \frac{\sqrt{2}.k}{3}\left(1 - cos(\pi \mathrm{BLD}.\Delta\lambda)\right) \ldots (7)$$

where $\Delta\lambda$ is the spacing between the modes as described above.

We can plot (7) and (2) as functions of the rms spectral width.

In conclusion, we see that the shape of the spectrum can change the level of mode partition noise penalty incurred in the link. However, we also see that a non-gaussian spectrum does not necessarily lead to higher mode partition noise penalty. In the case we have considered, the 3 mode spectrum, actually has a lower calculated MPN noise penalty than the Gaussian one.

More importantly, the impact of Mode Partition Noise kicks in only at long distances (km range) and very high spectral widths.

Effect of temperature on Spectral width

A commonly observed phenomenon is that Spectral width of a VCSEL changes over temperature.

The L-I curve of a laser shifts with temperature and depending on the drive current, the number of lasing modes could increase *or* decrease with temperature.

However, predicting the temperature behavior of spectral width can be a difficult process. In VCSELs, the cavity gain maximum and the wavelength of the cavity modes have different temperature coefficients. This is further complicated by the fact that when the VCSEL is used as a transmitter, the laser light output and amplitude modulation are maintained constant through various electronic feedback circuits. Hence the drive current and the modulation current fed to the VCSEL in a module change over temperature.

The following curves show the temperature dependence of spectral width measured on a few Agilent modules.

Spectral Width performance of Agilent MM Transceivers

Since spectral width is an important parameter for the performance, and yet is difficult to test at production level, it is important to have a screening process in place that effectively eliminates modules falling out of spec. Agilent has screens at both the VCSEL production level and at the module level to ensure that the rms spectral width of Agilent laser transmitters is within the specified Gigabit Ethernet target.

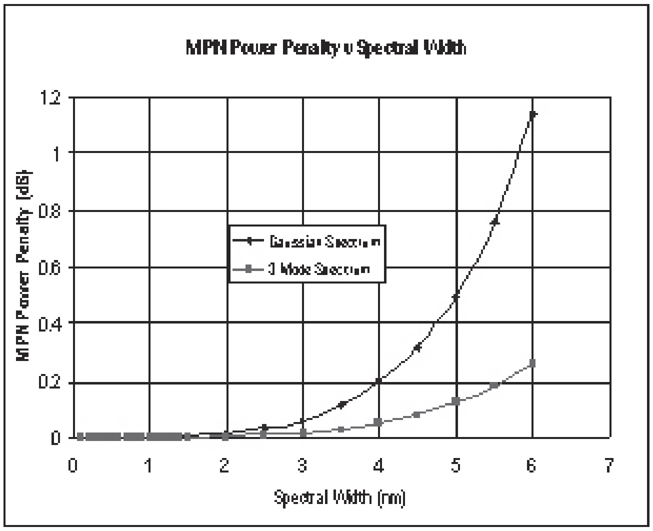

Figure 5. MPN Power Penalty versus Spectral Width

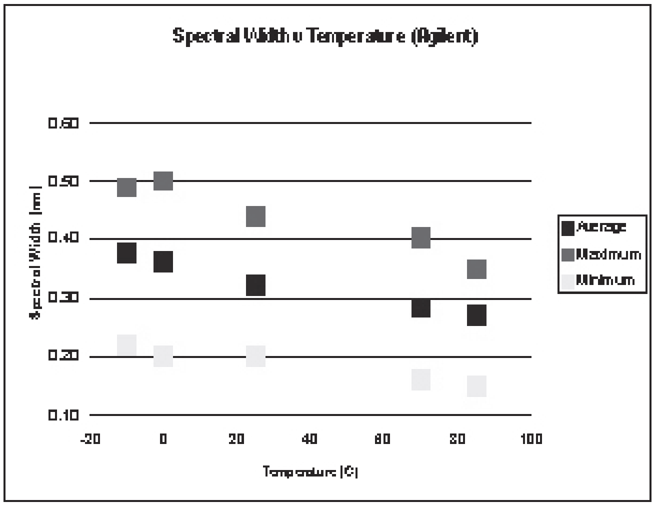

Figure 6. Effect of Temperature on Spectral Width

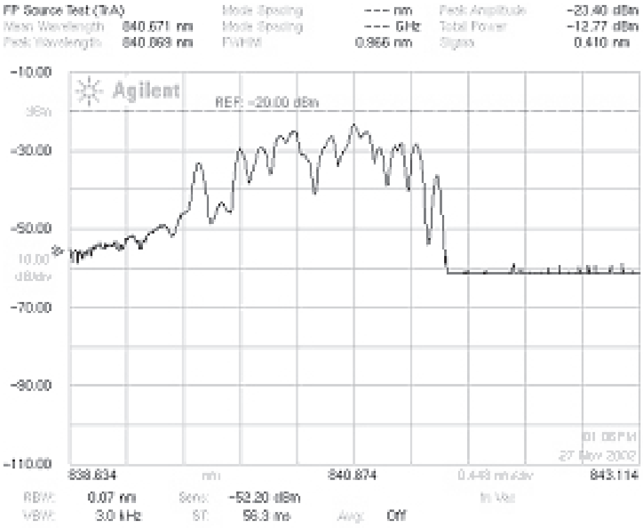

Figure 7. Agilent VCSEL optical spectrum

Discussion

The impact of spectral width on link performance has been discussed. It is observed that as long as the spectral width is within the specified value, it does not affect the link length by much. The shape of the optical spectrum is also not a direct indicator of the MPN. Hence, the rms value of the optical spectrum is the most important parameter to control.

Recognizing the need to keep spectral width within desirable limits, Agilent has a established a screening process that controls the spread of spectral width.

References

1. IEEE Document, 802.3, Section 1.4.238, page 27
2. Product Data Sheet, "Agilent 86140-series optical spectrum analyzers", http://www.agilent.com
3. IEEE Document, 802.3, Section 3, page 106
4. Govind P. Agrawal et al., "Dispersion Penalty for 1.3 mm Lightwave Systems with Multimode Semiconductor Lasers", Journal Of Lightwave Technology, Vol 6, 5, May 1998.

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