Optical Units Reference

Multipliers, Optical Power, Gain & Loss, Wavelength & Frequency, and Bandwidth & Optical Modulation Bandwidth

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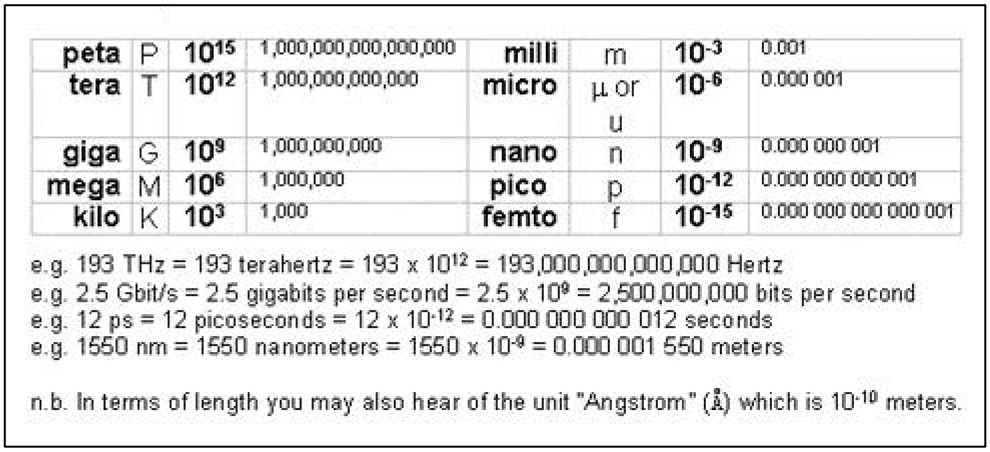
Here is a guide to the world of units used within the optical interconnect industry. This field can be confusing at the best of times, but when it comes to numbers and units the situation can often get critical. Misunderstandings can arise because of the different definitions used in different disciplines. After reviewing this reference, however, you will hopefully gather a basic units understanding and how they are applied.

The first concept to grasp are multipliers. Engineering personnel can quickly move themselves into a conversation that can sound greek by referring to orders of magnitude with word prefixes. The table below can be used to decipher typical optical prefixes. Words like terabit can now be interpreted to mean an optical signal that carrys a trillion bits of information per second.



peta	P	10^{15}	1,000,000,000,000,000	**milli**	m	10^{-3}	0.001
tera	T	10^{12}	1,000,000,000,000	**micro**	µ or u	10^{-6}	0.000 001
giga	G	10^{9}	1,000,000,000	**nano**	n	10^{-9}	0.000 000 001
mega	M	10^{6}	1,000,000	**pico**	p	10^{-12}	0.000 000 000 001
kilo	K	10^{3}	1,000	**femto**	f	10^{-15}	0.000 000 000 000 001

e.g. 193 THz = 193 terahertz = 193 x 10^{12} = 193,000,000,000,000 Hertz

e.g. 2.5 Gbit/s = 2.5 gigabits per second = 2.5 x 10^{9} = 2,500,000,000 bits per second

e.g. 12 ps = 12 picoseconds = 12 x 10^{-12} = 0.000 000 000 012 seconds

e.g. 1550 nm = 1550 nanometers = 1550 x 10^{-9} = 0.000 001 550 meters

n.b. In terms of length you may also hear of the unit "Angstrom" (Å) which is 10^{-10} meters.

Table 1: Unit Multipliers

Optical power is a critical measurement to understand when dealing with any system architecture. Optical power can typically be equated directly to system costs. The more optical power required the more money would be typically spent within a system. Low power systems utilize low cost optical lasers; high power systems can utilize lasers costing hundreds of thousands of dollars. Optical power is usually expressed in Watts (W). For anyone with an interest in physics power is actually energy per unit time, or Joules per second (J/s). In the field of optical networks, powers can be extremely small, so they will usually be given in units of milliwatts (mW) or decibels relative to a milliwatt (dBm). The dBm unit is commonly used and provides several advantages in calculations that make it easier to work with (see Gain & Loss below). If you are interested in the math, here are the equations for converting from mW to dBm and vice versa. A conversion table to help shield you from the mathematics is also provided.

$$\text{Power\_in\_dBm} = 10 \cdot \log\left(\frac{\text{Power\_in\_mW}}{1\ \text{mW}}\right)$$

$$\text{Power\_in\_mW} = 10^{\left(\frac{\text{Power\_in\_dBm}}{10}\right)} \cdot 1\ \text{mW}$$

Figure 1: Optical Power Calculation

dBm	mW		dBm	mW		dBm	mW
-30	0.0010		-10	0.1000		12	15.8489
-28	0.0016		-8	0.1585		14	25.1189
-26	0.0025		-6	0.3000		16	39.8107
-24	0.0040		-4	0.3981		18	63.0957
-22	0.0063		-2	0.6310		20	100.0000
-20	0.0100		0	1.0000		22	158.4893
-18	0.0158		2	1.5849		24	251.1886
-16	0.0251		4	2.5119		26	398.1072
-14	0.0398		6	3.9811		28	630.9573
-12	0.0631		8	6.3096		30	1000.0000
			10	10.0000			

Table 2: Optical Power Conversion

Key Concepts to understand are:

- Negative dBm powers are less than 1 mW
- 0 dBm is 1 mW
- The "logarithmic" nature of the equations means that small increases in dBm can give relatively small or large increases in mW

Knowing that optical power is a critical parameter in any system design, concerns about gains or losses in power are a natural by product. Any device that introduces a loss in a system (such as a connector) will typically be considered bad, any device that could provide a free gain would be considered good. LumaCon optical interconnects differentiate themselves from other optical interconnects by providing a lower loss when they are inserted into an optical system. In particular this is true of their performance relative to interconnects such as ribbon MT connectors. Gain or loss is usually expressed in decibels (dB) and is a change in optical power, not an optical power itself. It relates the input power to the output power, and is given by the following equation.(You should always ensure that both the powers entered into the equation are expressed in the same unit; e.g., both must be in mW or both must be in W, etc.)

$$dB = 10 \cdot \log\left(\frac{Power\_in}{Power\_out}\right)$$

Figure 2: Gain or Loss Equation

Key Points to retain are:

- A gain of 3 dB corresponds to the optical power (in Watts) doubling
- A loss of 3 dB (which can also be called a –3 dB gain) corresponds to the optical power in Watts halving
- Loss and gain of optical powers can be calculated quickly by just adding or subtracting the dB of gain or loss to the optical power in dBm, e.g:
  - If an optical power of -2 dBm experiences a gain of 8 dB, the resulting optical power is now 6 dBm
  - If an optical power of 4 dBm experiences a loss of 9 dB, the resulting optical power is now -5 dBm

Having this information regarding units of measure of optical power one can now begin to review more complex phenomena within optical systems, the actual movement of data within a waveform. Within a specific optical path data is moved at a specific frequency of light. For each light there is a wavelenth. A wavelength (or “lambda”) is the distance between two peaks or two troughs of a wave, and is measured in meters (m). Optical communications systems use light from the infrared spectrum and are considered very short wavelength (hence high frequency). Optical wavelengths, usually expressed in nanometers (nm).

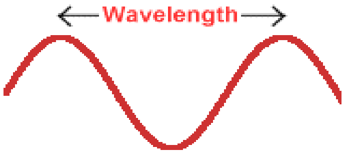


Figure 3. Wavelength Image

Often engineers will slip back and forth in discussion and seem to talk about wavelength and frequency within the same topic. This is because the two are inherently related. Frequency equals the number of waves that pass a fixed point in one second, designated by the unit of Hertz (Hz). The frequency of a wave is just the speed of light divided by the wavelength (the speed of light is about 300,000 km/s in a vacuum). With this equation you can see that smaller wavelengths have higher frequencies, and longer wavelengths have lower frequencies. Optical communications wavelengths of around 1555 nm relate to frequencies of around 193 THz.

$$\mathrm{Frequency\_in\_Hz} = \frac{\mathrm{Speed\_of\_light}}{\mathrm{Wavelength\_in\_m}}$$

$$\mathrm{Wavelength\_Separation} = \frac{\mathrm{Frequency\_Separation} \times \mathrm{Wavelength}^2}{\mathrm{Speed\_of\_light}}$$

Figure 4: Wavelength and Frequency Relationship

The latest optical networking systems do not operate with a single frequency but instead operate over a frequency band. The frequency band is typically broken in to many sub-bands. Each sub-band can be operated independently, to carry data as appropriate. This ability to operate with multiple frequency bands can be related to wavelengths as noted above and in the optical field this has become known as WDM or wavelength-division-multiplexing. WDM systems have the ability to add or drop specific wavelengths (or frequencies) at specific network node points (routers or switches). Hence a single optical fiber can carry a multitude of optical signals limited only by the ability to divide the frequency band with tunable lasers and stay within operating bands of the optical fiber. Below is the table converting typical WDM (wavelength-division multiplexing) frequency spacing into wavelength spacing. The three figures most often encountered are tabled below, along with some wavelength and frequency conversions for standard WDM channels with 100 GHz spacing.

		WDM Frequency Spacing	WDM Wavelength Spacing		
		100 GHz	0.8 nm		
		50 GHz	0.4 nm		
		25 GHz	0.2 nm		
WDM Wavelength (nm)	**WDM Frequency (THz)**	**WDM Wavelength (nm)**	**WDM Frequency (THz)**	**WDM Wavelength (nm)**	**WDM Frequency (THz)**
1539.766	194.7	1550.116	193.4	1560.606	192.1
1540.557	194.6	1550.918	193.3	1561.419	192.0
1541.349	194.5	1551.721	193.2	1562.233	191.9
1542.142	194.4	1552.524	193.1	1563.047	191.8
1542.936	194.3	1553.329	193.0	1563.900	191.7
1543.730	194.2	1554.134	192.9	1564.679	191.6
1544.526	194.1	1554.940	192.8	1565.496	191.5
1545.322	194.0	1555.747	192.7	1566.314	191.4
1546.119	193.9	1556.555	192.6	1567.133	191.3
1546.917	193.8	1557.363	192.5	1567.952	191.2
1547.715	193.7	1558.173	192.4	1568.773	191.1
1548.515	193.6	1558.983	192.3	1569.594	191.0
1549.315	193.5	1559.794	192.2	1570.416	190.9

Table 2: WDM Wavelength and Frequency Relationships

Very often when discussing networking systems the terms of the operating frequency or wavelength are often suppressed. Instead nomenclature moves toward the amount of raw information that can be transmitted through networks. This is typically quoted in bits per second and, more usually today, gigabits per second. This quantity can be referred to by many different names such as bit-rate, capacity, throughput, and bandwidth. However, in optical systems there is also another meaning for bandwidth that should be considered as unlike electrical systems the bandwidth is very much related to optical power and loss as described above.

Most data move through networks today is initiated with an electronics based system not an optically based system. Hence, the electrical signals must be converted into optical signals. The devices that accomplish this task are know as modulators. Modulators utilize special materials that switch a light stream passing through them on and off when an electrical current is applied to it. This electrical current corresponds to the information that is to be transmitted through the network as 1's and 0's and is generated by the aforementioned electronics based systems. Modulators by definition have a "bandwidth" associated with them. In optical systems the bandwidth is associated with the optical loss. Hence, a modulators capability can also be referred to by other names such as modulation bandwidth, optical modulation bandwidth, or 3dB modulation bandwidth.

As modulators basically have to switch a light on and off thousands of times every second, this modulation capability is expressed in the frequency units of Hertz (Hz). At very low frequencies (which correspond to low bit-rates of information) modulators perform very well, giving a very clear distinction between 1s (light) and 0s (no light) in their output. As the frequency at which they are driven increases, however, their performance suffers. A frequency is reached (hopefully at many GHz, matching the bit-rate of a system) at which the difference in light power between the 1's and 0's has dropped to half of the value it was at the very low frequencies. This is the so-called "optical modulation bandwidth." A 50 percent reduction in power corresponds to a 3dB loss (as described in the Gain and Loss section), which is why the figure can also be referred to as "3dB modulation bandwidth."

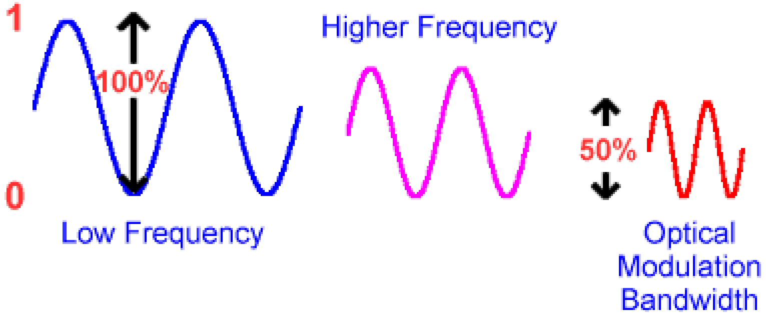


Figure 4: Modular Bandwidth

It is crucial to understand the idea of bandwidth versus data capability as the two are not the same when talking about data movement. A 10-Gbit/s modulator does not necessarily have a 12 GHz bandwidth. The bandwidth as noted above is a function of the modulator design and its processing quality. For instance in reality a 10-Gbit/s modulator may have a bandwidth around 12 GHz, and the figure may be around 30 GHz for a 40-Gbit/s modulator. It is critical to note that the relationship between bandwidth and data capability above as it illustrates that a higher data rate modulator may consume less bandwidth on a per Gbit/s basis than a slower modulator. This is important for system architects when consideration of WDM is taken as the optical spectrum available on the fiber is divided not by data capability but rather by bandwidth and there is only so much bandwidth available versus an ever growing demand for data capability.