Application Note:

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Optical Modulation Amplitude (OMA) and Extinction Ratio

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1 Introduction

The optical modulation amplitude (OMA) of a signal is an important parameter that is used in specifying the performance of optical links used in digital communication systems. The OMA directly influences the system bit error ratio (BER). With an appropriate point of reference (such as average power), OMA can be directly related to extinction ratio.

The purpose of this application note is to define OMA and how it relates to other parameters such as extinction ratio and average power. Further, this application note will clarify the trade-offs between specifying OMA versus extinction ratio and explore appropriate specification ranges for each.

2 Definitions and Relationships

For bi-level optical signaling schemes, such as nonreturn-to-zero (NRZ), only two discrete optical power levels are used. The higher level represents a binary one, and the lower level represents a zero. We will use the symbol P_1 to represent the high power level and the symbol P_0 to represent the low power level. Using these symbols we can mathematically define a number of useful terms and relationships.

OMA is defined as the difference between the high and low levels, which can be written mathematically as:

$$OMA = P_1 - P_0 \qquad (1)$$

Average power is simply the average of the two power levels, i.e.,

$$P_{AVG} = \frac{P_1 + P_0}{2} \qquad (2)$$

We will use r_e to represent the extinction ratio, which is the ratio between the high and low power levels:

$$r_e = \frac{P_1}{P_0} \qquad (3)$$

Through algebraic manipulation of equations 1, 2, and 3, we can derive the following relationships:

$$OMA = 2P_{AVG}\left[\frac{r_e - 1}{r_e + 1}\right] \qquad (4)$$

$$r_e = \frac{OMA}{P_0} + 1 \qquad (5)$$

$$P_1 = P_{AVG} + \tfrac{1}{2}OMA = 2P_{AVG}\left[\frac{r_e}{r_e + 1}\right] \qquad (6)$$

$$P_0 = P_{AVG} - \tfrac{1}{2}OMA = 2P_{AVG}\left[\frac{1}{r_e + 1}\right] \qquad (7)$$

3 Absolute Versus Relative Specs

OMA and extinction ratio by themselves are relative quantities, since they only specify the difference or ratio of the power levels. In order to derive an absolute quantity from the OMA or extinction ratio, we must have an additional point of reference, such as P_{AVG}, P_1, or P_0. The relationships of equations 4-7 all depend on one of these absolute points of reference.

For example, an OMA of 100μW can correspond to an infinite number of possible values for P_{AVG}, P_1, or P_0: P_1 could be 100μW with P_0 equal to 0μW, or P_1 could be 150μW with P_0 equal to 50μW, or P_1 could be 100mW with P_0 equal to 99.9mW, etc., etc.

In the alternate case of extinction ratio, a similar example using r_e=10 can correspond to an infinite number of possible values for P_{AVG}, P_1, or P_0: P_1 could be 100μW with P_0 equal to 10μW, or P_1 could be 150μW with P_0 equal to 15μW, or P_1 could be 100mW with P_0 equal to 10mW, etc., etc.

If, in addition to the OMA or extinction ratio, we specify a reference point of P_{AVG} = 100µW, for example, then the ambiguity is gone. With an OMA of 100µW and P_{AVG} = 100µW, P_1 can only be 150µW and P_0 can only be 50µW. If the extinction ratio is 10 and P_{AVG} = 100µW, then P_1 can only be 182µW and P_0 can only be 18.2µW.

4 Optical Attenuation

Up to this point in the discussion, it may seem apparent that OMA and extinction ratio are basically equivalent. Either can be computed with knowledge of the other and one reference point. Both can be quantified when the values of P_1 and P_0 are known, etc. There are differences, however, and one of these is how OMA and extinction ratio change as the signal propagates through an optical system.

Assuming a system with linear attenuation between two points, the extinction ratio will stay constant even though the signal is attenuated, while the OMA will change by a factor equal to the attenuation. For example, over 10km of optical fiber with an attenuation of 0.3dB/km, the total attenuation over the length of the fiber is 3dB, which is equivalent to a factor of 2. If we transmit a signal through the fiber that starts with P_1 = 1mW and P_0 = 0.1mW, then r_e = 1/0.1 = 10 and OMA = 1 – 0.1 = 0.90mW at the fiber input. After passing through the fiber the signal levels are reduced by a factor of 2, so P_1 = 0.5mW and P_0 = 0.05mW. Therefore, at the fiber output, r_e = 0.5/0.05 = 10 (the same as at the input r_e) and OMA = 0.5 – 0.05 = 0.45mW (half of the input OMA). From this example we see that once the extinction ratio is known, a simple average power measurement anywhere in the system will yield enough information to calculate P_1, P_0, and even OMA. On the other hand, if we have knowledge of the OMA at one point in the system, we cannot determine it's value after attenuation without knowing the magnitude of the attenuation or else measuring additional parameters (such as P_0, P_1, or P_{AVG}).

5 Power-Level Effects on Transmitters and Receivers

In theory, the system bit error ratio (BER) is determined entirely by the optical signal-to-noise ratio, which is commonly called the Q-factor (see Maxim application note HFAN-9.0.2 "Optical Signal-to-Noise Ratio and the Q-Factor in Fiber-Optic Communication Systems"). The Q-factor is defined as the OMA divided by the sum of the rms noise on the high and low optical levels, i.e.,

$$Q = \frac{P_1 - P_0}{\sigma_1 + \sigma_0} \tag{8}$$

Based on equation 8 (and assuming that the noise is a fixed quantity) it is clear that the system BER performance is directly controlled by the OMA. Therefore, in order to optimize BER performance, the OMA should be as large as possible. Also, equation 8 says nothing about P_{AVG}, implying that we will get the same BER performance whether P_1 and P_0 are 100mW and 1mW or 200mW and 101mW. In real systems, there are practical upper and lower practical limits on P_{AVG} and therefore OMA.

From the optical receiver point of view, there is an upper limit on the optical power that can be received called the overload level. When the power exceeds this level, saturation effects degrade performance. This means that for optimum receiver BER performance, the OMA should be as large as possible while avoiding overload, which occurs when P_0 = 0 and P_1 is just below the overload level. In this case, OMA=$P_{OVERLOAD}$, P_{AVG}≈0.5×$P_{OVERLOAD}$ and $r_e = \infty$. If P_0 > 0, then the OMA must be reduced to avoid overloading the receiver.

From the optical transmitter point of view, it is very difficult to reduce P_0 to zero. When the laser is quickly switched from the completely off state to the on state it causes negative effects such as turn-on delay and relaxation oscillation. If the laser is biased above its threshold level then it is always slightly on, and problems with turn-on delay and relaxation oscillation decrease as the bias level is increased. For this reason, practical transmitters emit some optical power at P_0. A complicating factor is that the laser threshold changes significantly with temperature, so, if the difference between the bias and threshold is to remain constant, the bias current must be adjusted as the temperature changes. Precise control of the bias current over a large temperature range adds significant complexity and cost to the transmitter.

When we consider both the optical transmitter and the receiver, it is apparent that P_0 should be kept as low as possible without getting so low that it causes problems with the laser. If P_0 is increased much beyond this point, power is wasted and receiver performance is potentially degraded. Using these arguments we can define upper and lower practical limits for P_0.

6 Practical Power Limits

As noted in the previous section, it is generally not practical to achieve the ideal level of low power, i.e., $P_0 = 0$. When P_0 is raised above the ideal, however, the average power must be increased with no corresponding increase in system BER performance. The ratio between the average power transmitted by a particular real optical system and the average power that would be required in the ideal case (to achieve the same BER) is called the power penalty.

When specifying the OMA of an optical communication system, it is important to consider the potential power penalty due to the difference between P_0 and 0. While this difference can be specified directly, it is more useful to specify P_0 as a ratio to the OMA. This is because the ability to control P_0 to a given level of precision is related to the magnitude of the OMA. Also, it is more informative to think of the power penalty in terms of a ratio between the OMA and P_0. For example, if the OMA is specified to be very large (e.g., 10mW), then controlling P_0 to within a very small fraction of the OMA (e.g., 1µW above zero) achieves very little benefit and is very difficult. Also, the power penalty associated with a 1µW variation in P_0 would be insignificant relative to an average power on the order of OMA/2 = 5mW. For these reasons, P_0 should be specified as a ratio to the OMA, and a convenient way to do this is the OMA to P_0 ratio. Thus, if P_1 = 180µW and P_0 = 20µW, the OMA = 180 – 20 = 160µW and the OMA to P_0 ratio is 160µW/20µW = 8. This corresponds to an extinction ratio of r_e = 180µW/20µW = 9. The general relationship between extinction ratio and the OMA to P_0 ratio can be derived through manipulation of equation (5) as:

$$r_{Po} = \frac{OMA}{P_0} = r_e - 1 \qquad (9)$$

where r_{Po} represents the OMA to P_0 ratio. For the ideal case (where $P_0 = 0$), $r_{Po} = \infty$ and $r_e = \infty$.

As mentioned above, the ratio between the actual average power transmitted by an optical system and the average power that would be required in the ideal case (to achieve the same BER) is called the power penalty. This can be written as:

$$\delta_{Po}(r_{Po}) = \frac{P_{AVG}(\text{actual } r_{Po})}{P_{AVG}(r_{Po} = \infty)} = \frac{r_{Po} + 2}{r_{Po}} \qquad (10)$$

where $\delta_{Po}(r_{Po})$ represents the power penalty in terms of the OMA to P_0 ratio. Alternately,

$$\delta_e(r_e) = \frac{P_{AVG}(\text{actual } r_e)}{P_{AVG}(r_e = \infty)} = \frac{r_e + 1}{r_e - 1} \qquad (11)$$

where $\delta_e(r_e)$ represents the power penalty in terms of extinction ratio.

As an example of power penalty calculation, we can use the values from the previous example (where P_1 = 180µW, P_0 = 20µW, OMA = 160µW, r_{Po} = 8, and r_e = 9). In this case, the power penalty in terms of r_{Po} is $\delta_{Po}(r_{Po}) = (8+2)/8 = 1.25$ or, in terms of r_e, $\delta_e(r_e) = (9+1)/(9-1) = 1.25$. This means that the actual power transmitted is 1.25 times greater than it would be in the ideal case where $P_0 = 0$ and $r_{Po} = r_e = \infty$.

Maxim application note HFAN-2.2.0: Extinction Ratio and Power Penalty, includes the following graph of extinction ratio versus power penalty.

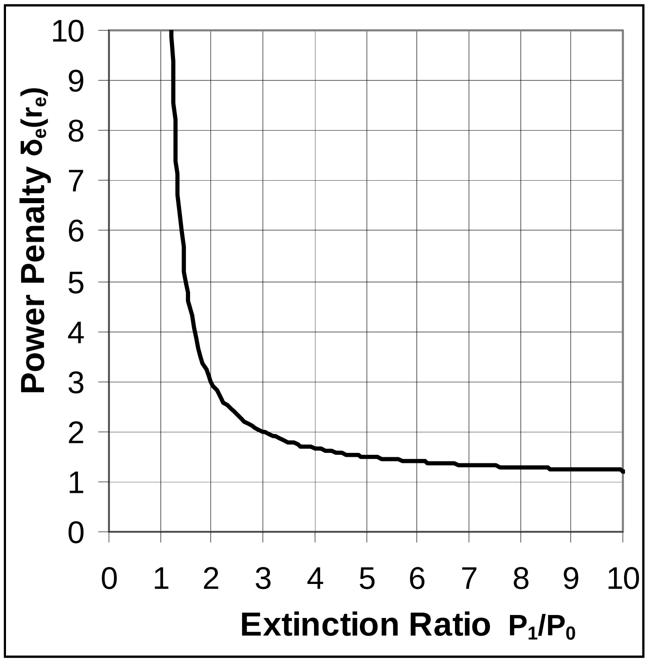

Figure 1. Power Penalty Versus Extinction Ratio

Through the end of this section we will neglect reference to the OMA to P_0 ratio, remembering that it is equivalent to the extinction ratio minus one.

From Figure 1 and equations (10) and (11), we can make some important conclusions about the practical limits on extinction ratio. First, we recall from the previous section that very high extinction ratios cause many problems for the transmitter. In general, the practical limit on extinction ratio for a transmitter is in the range of 10 to 12. From equation (10) we note that the power penalty for $r_e = 10$ is 1.22 and for $r_e = 12$ it is 1.18. While the increased complexity and expense of the transmitter is usually quite significant to achieve $r_e = 12$ versus 10 (especially over a large temperature range), the savings in power is 4%. If we limit the power penalty and extinction ratio numbers to one decimal place (measurement of these quantities to more precision than this is difficult and unreliable) we see that the power penalty remains at a constant 1.2 for extinction ratios between 9.1 and 14.4. If we allow a 10% degradation to a power penalty of 1.3 (rounded to one decimal place), then the corresponding range of extinction ratio is 6.7 to 9.0. This relationship between ranges of extinction ratio and power penalty rounded to one decimal place is tabulated in the following table:

TABLE 1. Extinction Ratio Ranges Versus Power Penalty Rounded to One Decimal Place

r_e	r_e (dB)	$\delta_e(r_e)$
3.0 - 3.1	4.8 - 5.0	2.0
3.2 - 3.3	5.1 - 5.2	1.9
3.4 - 3.6	5.3 - 5.6	1.8
3.7 - 4.0	5.7 - 6.0	1.7
4.1 - 4.6	6.1 - 6.6	1.6
4.7 - 5.4	6.7 - 7.3	1.5
5.5 - 6.6	7.4 - 8.2	1.4
6.7 - 9.0	8.3 - 9.5	1.3
9.1 - 14.4	9.6 - 11.6	1.2

From Figure 1 and Table 1 we can see that the practical lower limit on power penalty is approximately 1.2, which corresponds to an extinction ratio in the 9 to 14 range. If we can accept a 10% degradation in power penalty from the 1.2 level, then any extinction ratio greater than 6.6 (8.2dB) will do.

As far as the lower practical limit on extinction ratio, we see that, for extinction ratios below 6.6 (8.2 dB), the power penalty increases by at least 10% for an extinction ratio change of one. When the extinction ratio is 3, the power penalty is 2.0 (meaning we are wasting half of the power). When the extinction ratio is less than 3, the power penalty increases dramatically, thus the extinction ratio should always be kept above 3.

7 Summary

1. Optical Modulation Amplitude (OMA) is an important quantity that is directly related to the system Bit Error Ratio (BER).

2. OMA and extinction ratio are relative quantities that can be mathematically related to each other only if we have an absolute point of reference, such as P_0 or average power.

3. Extinction ratio does not change as the optical signal is linearly attenuated. Attenuation does change the OMA by a factor equal to the attenuation.

4. In an ideal system, the zero-level optical power is zero (i.e., $P_0 = 0$). This results in optimum power efficiency and system BER.

5. In a laser-based transmitter, it is not practical to set $P_0 = 0$. Setting P_0 too close to zero causes turn-on delay, relaxation oscillation, etc. Constructing a transmitter that maintains P_0 very close to zero over a large temperature range can be very difficult and expensive.

6. Either the OMA to P_0 ratio or the extinction ratio can be used in specifying the transmitter performance relative to the $P_0 = 0$ level. These two parameters are essentially equivalent.

7. The practical upper limit on extinction ratio is in the range of 10 to 12, which corresponds to an OMA to P_0 ratio of 9 to 11. Transmitter complexity (and therefore cost) can be greatly reduced if the extinction ratio requirement is reduced. The trade-off is increased optical power requirements for the same BER performance. Reducing the extinction ratio requirement from the 10 to 12 range to a minimum of 6.6 (8.2dB) results in an optical power increase of approximately 10%.

8. The absolute lower practical limit on extinction ratio is approximately 3, which corresponds to an OMA to P_0 ratio of 2. At this level one-half of the optical power is wasted. Below this level the power penalty increases tremendously.